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FLOC STRENGTH AND FILTERABILITY OF PRETREATED WATER

Ludwig Engineering and Science Research Foundation
Arcadia, California

November 1967

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ANNUAL REPORT
PROJECT YEAR 1966-1967

FLOC STRENGTH AND FILTERABILITY OF PRETREATED WATER

RESEARCH GRANT WP-00813-01

Prepared For

FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
DEPARTMENT OF INTERIOR

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LUDWIG ENGINEERING AND SCIENCE RESEARCH FOUNDATION

150 EAST FOOTHILL BOULEVARD, ARCADIA, CALIFORNIA

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ABSTRACT

FLOC STRENGTH AND FILTERABILITY
OF PRETREATED WATER

The significance of floc strength in the filtration process was reviewed, and two methods for its measurement were developed. Of the two, the measurement of the median size of the floc following fragmentation under high shear stress was considered to represent floc strength reasonably well. pH and coagulant dosage were found to affect the strength of floc as measured by this method.

In order to correlate floc strength with performance of a filter the Filter Run Index (t_1-t_2/t_1+t_2) was developed in which t_1 represents the time of floc breakthrough and t_2 is the time required to reach a limiting headloss. The Index is a measure of the compatibility of a floc to a particular filter as well as a measure of the filter performance. The rationale of the Index was discussed. Field surveys of local water treatment plants showed that the degree of floc penetration and the length of filter runs are significantly affected by the strength of the floc.

A water treatment pilot plant was constructed having a capacity of 1.0 gpm. It has four filter columns as well as pretreatment units. The effect of floc strength on filter performance will be investigated under controlled conditions during the next project year.

LUDWIG ENGINEERING AND SCIENCE RESEARCH FOUNDATION

HEADQUARTERS
150 EAST FOOTHILL BLVD.
ARCADIA, CALIFORNIA 91006
RESEARCH AND DEVELOPMENT LABORATORY
4144 TELEGRAPH AVENUE
OAKLAND, CALIFORNIA 94609

HARVEY F. LUDWIG, PRESIDENT

30 November 1967

Dr. Harry A. Faber
Research and Training Grants Program
Federal Water Pollution Control Administration
Department of the Interior
Washington, D. C. 20201

Dear Dr. Faber:

This will transmit our report for the contract year 1966-67 pursuant to the terms of Research Grant WP-00813-01, Federal Water Pollution Control Administration, Department of the Interior.

The significance of floc strength in the filtration process was reviewed and two methods for its measurement were developed. Of the two, the measurement of the median size of the floc following fragmentation under high shear stress was considered to represent floc strength reasonably well. pH and coagulant dosage were found to affect the strength of floc as measured by this method.

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Sincerely yours,

Harvey F. Ludwig

Harvey F. Ludwig
Ludwig Engineering and Science
Research Foundation

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CHAPTER I

INTRODUCTION

This annual report summarizes research conducted during the period from 25 May 1966 to 24 May 1967 by the Ludwig Engineering and Science Research Foundation. The research project was devoted to the development of reliable methods for quantitating the strength of coagulant flocs employed for water treatment purposes, demonstrating the relationship of floc strength to filterability, and correlating the results of water treatment plant practices with conclusions developed from the laboratory research. A laboratory pilot plant constructed for continuing studies is also described in this report.

SIGNIFICANCE OF FLOC STRENGTH IN WATER TREATMENT

Definition of Floc Strength

Flocs formed by the addition of coagulants to an aqueous system constitute the results of a complex series of events, both physical and chemical, which involve the properties of the solvent (water), the "solute" (ions, organic materials, colloids, and particulates), and the coagulant. Initial floc formation (primary flocs) is primarily a chemical phenomenon, which consists of charge neutralization and aggregation through collisions brought about by Brownian motion. Brownian motion is a dominant mechanism for aggregation until the flocs reach a size of approximately 0.1 micron. Thereafter, velocity gradients generated by mixing devices or other means of energy input effect further collisions between the primary flocs, causing the formation of larger aggregates designated as secondary flocs (Reference 1).

The bonding forces within the primary flocs are considered to be stronger than the bonding forces between the primary flocs. When the applied shear stress is greater than the cohesive force of an aggregate floc, the floc will be fragmented into the smaller sizes. The practical upper size limit for coagulant flocs in water treatment facilities is in the range of 100 to 2,000 microns (Reference 2), and for a given situation this upper limit is determined by the cohesive forces between primary flocs making up the secondary floc and shearing stresses imposed on the floc by velocity gradients in the fluid medium.

The floc strength can be defined as the ability of an aggregate or secondary floc to withstand shearing stresses (which may be applied during both flocculation and filtration operations). By knowing the shear stress applied and the sizes of fragmented flocs, it is possible to estimate the effective cohesive forces within the aggregate flocs. Therefore, floc strength can be quantitated for any system.

Effect of Floc Strength in Rapid Sand Filtration Process

The removal of floc in a filter such as a deep sand bed is called depth filtration, and the removal is achieved by the attachment of floc to individual

media grains. From a practical standpoint two factors are of major concern in the operation of a rapid sand filter. The first concerns the efficiency of floc removal by a unit volume of filter media while the second is the headloss limitation.

Considering the first aspect, the attachment of floc to filter media is due to the transport of flocs near to the sand grain where they are attached either to the sand grains or to the floc already attached. Since strong floc means strong cohesive force, the efficiency of attachment to media will be greater for the stronger flocs than for the weaker flocs. On the other hand, strong floc can resist shearing forces much better than weaker floc and may tend to plug the filter media leading to the cake filtration. For the weaker floc the efficiency of attachment may be lower but tends to be broken down when the interstitial velocity of the liquid increases, and the floc will be moved down to a lower level in the filter. Consequently, the weaker floc may serve to maintain pore openings much better than the stronger floc.

Cake filtration results in greater headloss than depth filtration and as a rapid sand filter has a limited hydraulic head available, it may be desirable to have weak flocs. On the other hand, weak flocs are undesirable from the standpoint of removal efficiency.

From these two opposing considerations it is suggested that an optimum floc strength may be found at some value which gives moderate removal efficiency and moderate headloss rate. The selection of the optimum floc strength for a given condition of depth filtration should lead to increased filtration runs and greater economy in water treatment plant operation (Reference 3).

Robeck et al (Reference 4) noted that adequate floc strength was one of the most important factors in the high rate filtration.

FACTORS AFFECTING FLOC STRENGTH

The following may affect floc strength.

Chemical Factors

1. pH
2. Type and concentration of coagulant dosage
3. Type and concentration of coagulant aid
4. Dissolved solids

Physcial Factors

5. Amount of energy input for flocculation
6. Intensity of mixing, i e., paddle geometry
7. Temperature of a suspension

Suspension Factors

8. Concentration of suspended solids
9. Type of suspended solids

It is impossible to evaluate all of these parameters in the present study and, therefore, emphasis will be placed on the first three parameters. Stumm and Morgan (Reference 5), O'Melia and Stumm (Reference 6) and others

showed the importance of the pH and the coagulant dosages in the coagulation process. Conley and Pitman (Reference 7) and Agrawal (Reference 8) demonstrated the important role of polyelectrolytes in the depth filtration while Weitser et al (Reference 9) showed how some polyelectrolytes strengthen the floc.

This choice, also, was made because they are easily controlled and are considered the most important factors in clarification operations. Other factors will be held constant to evaluate the effect of these three factors on the floc strength and filterability.

PROGRAM OF STUDY

To achieve the stated objectives six stages of the study were planned as follows:

1. Development of a method of floc strength measurement
2. Development of a method of filterability determination
3. Field survey of local water treatment plants to test these methods
4. Construction of a pilot plant
5. Operation of a pilot plant
6. Analysis of data

The first four stages are described in this report.

PROJECT STAFF

Participants in this study from Ludwig Engineering and Science Foundation are:

Dr. Harvey F. Ludwig, Project Director
Dr. Wonsuk Kim, Project Engineer
Mr. Stanley R. Primmer, Research Assistant
Mr. Taghi Manbeian, Research Assistant

ACKNOWLEDGEMENTS

Valuable assistance and advice rendered by the following individuals are greatly appreciated.

Dr. W. J. Kaufman, Professor of Sanitary Engineering, University of California, Berkeley, California.

Mr. Donald G. Larkin, Manager, Water Supply and Distribution Division, East Bay Municipal Utility District, Oakland, California

Mr. Gordon R. Laverty, Supervising Sanitary Engineer, Water Supply and Distribution Division, East Bay Municipal Utility District, Oakland, California.

Mr. William D. McGuire, Superintendent, North Area Water Treatment and Distribution Division, East Bay Municipal Utility District, Oakland, California.

CHAPTER II

METHODS OF FLOC MEASUREMENT

BONDING FORCES IN A FLOC

According to Michaels (Reference 2) floc can be divided into two groups.

Primary Floc

Generally the size of suspended particles are less than 10 microns. When coagulants are added to this suspension, the electrostatic charge of particles is reduced and they are bound together by the precipitate of aluminum hydroxo complexes, although sometimes particles are bound without the presence of alum precipitates. The primary floc is considered roughly spherical and it is the basic unit in a moderate shear field.

Aggregate Floc

At very low shear rates the primary particles cluster together to form larger particles. This is the aggregate floc and has relatively weak bonding forces. The floc in water treatment belong to this category. They have sizes ranging from 100 microns to 2,000 microns.

The bonding force within the primary floc may be electrostatic in nature while the bonding forces holding a cluster of primary flocs (or an aggregate floc) are probably weaker forces such as those of hydrogen bonding or Van der Waals forces.

In the flocculation process the growth of floc is promoted by providing a low intensity shear field. The shear force exerted is in the range of 0.2 - 0.75 dyne/cm^2 (Reference 10). In the succeeding filtration stage the shear force exerted on the floc is expected to go up to 8.9 dyne/cm^2 (Reference 11). Therefore, it can be pictured that the flocs leaving the pretreatment operations are aggregate flocs and the flocs leaving the filter are mostly of the primary type.

It is very difficult to measure the bonding forces within the floc directly. However, there are three indirect ways of measuring floc strength.

Size of Fragmented Floc

When aggregate flocs are subjected to a high shear field which exerts force greater than the bonding force holding the primary flocs together, they will be fragmented to smaller sizes. The stronger flocs will be fragmented less than the weaker flocs. Therefore, the average size of sheared flocs will give the indication of floc strength.

Permeability of a Layer of Floc

When liquid is passed through a layer of floc, strong floc may maintain the porosity under a constant pressure of filtration while the weaker floc

will tend to collapse and the porosity will be reduced. Therefore, the filter cake formed by the stronger floc may show the higher permeability than the same of the weaker floc.

Penetration of Floc Into a Filter Media

On a given depth filter media operated at a fixed filtration rate, the depth of floc penetration is greater than the penetration caused by the stronger floc. Therefore, the degree of penetration may indicate the floc strength.

METHODS OF FLOC STRENGTH MEASUREMENT

Particle Counting by the Coulter Counter

The Coulter Counter was originally made for the counting of red blood cells. The principle of this measurement is as follows: A capillary passage is made between two electrodes and electric current and particles pass through this narrow hole. The liquid medium contains relatively high salt concentration and current flows through this electrolyte solution. When a relatively non-conductive particle passes through the capillary hole the cross sectional area of the hole is temporarily reduced, causing reduction of current flow. The change of current or pulsation is recorded and the height of the pulse is correlated with the size of particle. Hannah (Reference 12) used this instrument to measure the size of fragmented alum floc.

The Coulter Counter was designed for red blood cells, and to extend its application to flocs formed by interaction of clay particles and alum may encounter the following difficulties:

1. This method requires 0.2 - 1.0 percent NaCl solution as the medium. This is a relatively high concentration compared to alum dosages which is usually less than 0.005 percent. Therefore the presence of NaCl in a suspension will affect coagulation behavior of certain suspended material. Hannah found that 0.2 percent NaCl did not affect coagulation behavior of kaolinite suspension. The effect of NaCl on a local runoff water was, however, not insignificant as shown in Figure II-1. This may be due to the high proportion of bentonite in the suspension.

2. When a floc approaches the capillary, the velocity gradient increases and fragmentation may result. This process of fragmentation will continue as it approaches the capillary hole and one cannot be sure at what stage of fragmentation the size distribution was measured.

There is no doubt that the Coulter Counter is one of the most convenient devices to measure particle size distribution. At the present time, however, the above mentioned difficulties need to be resolved for the application to alum flocs.

Incremental Turbidimetric Method

When flocs in suspension are subjected to a high shear field, they break down into smaller sizes and the subsidence rate of the particles decreases. Therefore, the turbidity of unsettled portions of a suspension will increase

after shearing. Hudson (Reference 1), Harris et al (Reference 13) applied this method in the study of flocculation kinetics. This method is a relatively simple method. In order to express the increment of turbidity in terms of floc strength some consideration may be necessary.

Weitser-Paskutskaia Method

This method (Reference 9) is based on the fact that the intensity of light scattering is in reverse proportion to particle size in coarse suspensions. Therefore, to a suspension, the varying speed and agitation were applied until the turbidity of the suspension does not increase any more. The minimum speed of mixing at which the breakdown of floc is complete is considered as an index of floc strength. They applied this method successfully on floc suspension formed by polyacrylamide and salts. However, it is not certain whether this method is sensitive enough to be used on the weaker floc such as alum floc, or not.

Photographic Method

The size distribution of floc was found by taking photographic pictures of the suspension in a dark background and counting the number of particles from the photograph. Gemmel and Fair (Reference 14) used this method in the study of flocculation kinetics. Some subjectiveness in the counting process may be inevitable. Also, the counting process may be time-consuming. This method, therefore, was not considered.

Floc Penetration Method

Hudson (Reference 15) and Stanley (Reference 16) studied the penetration of floc in a sand media. Hudson derived two equations to express floc strength.

Under laminar flow condition:

$$\text{Floc Strength Index} = \frac{Vd^3h}{l} \qquad (1)$$

Under turbulent flow conditions:

$$\text{Floc Strength Index} = \frac{Vd^2\sqrt{h}}{l} \qquad (2)$$

Stanley (Reference 16) obtained a somewhat different equation as follows:

$$k = \frac{V^{1.56}d^{2.56}h}{l} \qquad (3)$$

h = loss of pressure through a bed thickness, ft

l = depth of floc penetration, ft

V = velocity of flow, (ft/sec ?)

d = effective size of sand media, mm

Hudson (Reference 15) noted that equation (1) of laminar flow can be applied to weak flocs and equation (2) of turbulent flow can be applied to strong flocs. If his equation is to be used, one has to know whether the floc is weak or strong before the calculation. But the equations are to find the floc strength and one cannot presuppose the floc strength. Also, depending on the choice of the equation, the result of the floc strength index will be different. Another drawback is that it requires complete water treatment plant or a pilot plant to obtain necessary data for the calculation of floc strength index.

Permeability Method

Michaels et al (Reference 1) measured the permeability and porosity of settled beds of flocculated kaolinite at different pressures and found that some floc gave higher permeabilities than the others, even at the same porosity. This was interpreted that flocs of higher strength maintain their structure and provide for high permeabilities, while other flocs collapse and a reduced permeability results. The method requires the prior preparation of floc filtration mat for the test. This can be achieved on a highly concentrated clay suspension. But in water supply, the clay concentration is too low to obtain a measurable thickness of floc mat within reasonable time. There is another approach to solve this problem. This method was developed by Millipore Filter Co. and was called Silting Index Method (Reference 17). This method was also investigated in our study.

After the evaluation of several methods used by other investigators for the measurement of floc strength and particle size distribution, our interest was narrowed down to the silting index method and the incremental turbidity method.

SILTING INDEX METHOD

Silting Index Apparatus

According to the Millipore Filter Co. (Reference 17) the rate of clogging of suspended material (or contaminant) in a liquid can be indicated by the "Silting Index". The apparatus is shown in Figure II-2.

A measurement is made as follows: The sample is drawn into the syringe through a three-way valve up to the mark, "Fill". Then the valve is closed and a filter head containing a 0.8 μ pore Millipore Filter is attached at the bottom. A weight of 2.4 kg is placed on top of the plunger. The valve is then opened to the filter, and the times for the plunger to reach V_1, V_2, and V_3 are measured starting from the zero mark. The Millipore Filter Co. "Silting Index" is calculated as follows:

$$S.I. = \frac{T_3 - 2T_2}{T_1} \qquad (4)$$

T_1, T_2, and T_3 are the times to reach volumes V_1, V_2, and V_3, respectively, starting from the zero mark.

Modification of the Millipore Filter Co. Silting Index Method

The method suggested by the Millipore Filter Co. invclved the following difficulties as far as the present study was concerned:

1. In employing equation (4) for calculating the Silting Index, an assumption that the initial filtration rate (from zero to V_1) is approximately the same as the filtration rate of uncontaminated liquid was made. For relatively concentrated suspensions, this assumption is not valid.

2. The reproducibility was poor. It was found in our laboratory that the average of three successive measurements gave a 95 percent confidence interval of 17 percent (Millipore Filter Co. found 18 percent). This was partly due to the critical time, T_1, which was a short interval and difficult to reproduce.

3. For a fixed condition of measurement, i.e., fixed filter area and pore size and fixed applied pressure, the range of suspension concentration which could be measured within a reasonable length of time (less than 15 minutes) was narrow.

In order to overcome these difficulties the following modification was made. The total volume interval marked on the syringe barrel was first divided into 10 major and 20 minor subdivisions and so marked. Since the volume between zero and V_3 was 10.0 ml, each major division represented 1.0 ml. During a test the time that the plunger passed <u>each</u> major division was recorded instead of recording merely the time of passing V_1, V_2, and V_3.

From these data, t/V vs V was plotted (t was time and V was volume), and the slope of the linear regression line was calculated. This slope was proportional to the "Silting Index" as the following analysis shows.

Through the use of this modified method, more data can be collected during the same length of time than can be obtained using the Millipore Filter Co. method. Moreover, it is not necessary to wait until the plunger tip reaches V_3 for the calculation of "Silting Index", as long as four or more points are obtained in a straight line; this shortens the length of time required to make a test, even for relatively concentrated suspensions. In addition, the reproducibility in terms of 95 percent confidence interval is reduced from 18 percent to 10 percent, and there is no need to assume that the initial filtration rate is the same as that of the clear liquid.

Theory of Filtration and the Silting Index

The integrated form of Carman's equation for the filtration liquid suspensions is as follows:

$$\frac{t}{V} = \frac{\eta\,(rc)}{2PA^2}\,V + \frac{\eta\,Rm}{PA} \qquad (5)$$

$$\frac{t}{V} = b(rc)V + a \qquad (6)$$

t = time (duration) of filtration (sec)

V = volume of filtrate (ml)

η = viscosity (g/cm-sec)

P = pressure drop in filtration dyne/cm^2

A = area of filter (cm^2)

r = specific resistance of solid matter, cm/g when floc concentration is expressed as g/cm^3 and $\frac{1}{cm^2}$ when floc concentration is expressed as cm^3/cm^3.

c = concentration of solid (g/cm^3) or cm^3/cm^3

Rm = initial resistance of filter surface

$b = \eta/2PA^2$

$a = \eta Rm/PA$

According to equation (6) the graph of t/V vs V should indicate a linear relationship, with the slope of the line represented by bx(rc). The "Silting Index" was defined by equation (7) by the Millipore Filter Co.:

$$\frac{t}{V} = \frac{\eta S}{2PA^2} V + \frac{\eta Rm}{PA} \qquad (7)$$

Comparison of equations (6) and (7) yields the "Silting Index"

$$S = rc \qquad (8)$$

The calculation of the "Silting Index" by equation (7) as proposed by the Millipore Filter Co. is an approximate measure of S(= rc) and for which units were neglected. Henceforth, we will define the product of specific resistance, r, and concentration of solids, c, as "silting index" in lower case letters. This silting index can be found from the slope of t/V vs V and the calculation of b. In a similar manner, the specific resistance can be calculated from the slope and measurement of the solids concentration as shown in equations (9) and (10).

b(rc) = slope of t/V vs V plot

$$rc = \frac{\text{slope}}{b} = \text{silting index} \qquad (9)$$

$$r = \frac{\text{slope}}{bc} = \text{specific resistance} \qquad (10)$$

Relationship of Specific Resistance and Permeability

When the flow resistance exerted by the filter support is neglected, equation (5) becomes as follows:

$$\frac{V}{t} = \frac{2PA^2}{\eta(rc)V} \tag{11}$$

Darcy's equation of the flow through porous media is:

$$\frac{V}{t} = \frac{KPA}{\eta l} \tag{12}$$

K = specific permeability (cm^2)

l = thickness of porous media (cm)

From equation (11) and (12)

$$K = \frac{2}{(rc)} \quad \frac{Al}{V} \tag{13}$$

When c is expressed as volume fraction, cm^3/cm^3:

cV = volume of floc removed, cm^3

Al = volume of filter cake, cm^3

$\therefore cV = Al$

Therefore equation (13) becomes

$$K = \frac{2}{r} \tag{14}$$

According to equation (14) the specific resistance of a filter cake is the inverse of specific permeability when the floc concentration is expressed as a volume fraction. Measurement of floc volume is very difficult by itself, and it is easier to express floc concentration by weight. If weight concentration of floc is used, the dimension of specific resistance will be cm/g instead of $1/cm^2$.

Effect of Pressure on the Specific Resistance

According to equation (5) the specific resistance of floc should be independent of pressure drop across the filter cake. However, flocs are not completely rigid as was assumed in the deviation of Carman's equation. The effect of pressure on the specific resistance needs to be established because the measured value of specific resistance may differ depending on the pressure applied for the measurement.

The silting index apparatus supplied by Millipore Filter Co. has a weight of 2.4 kg. This exerts a pressure of 20 psig to a filter (Millipore Filter, 0.8μ pore) while the hydrostatic pressure on a surface of a rapid sand filter is about 1.3 psig (3 ft of water or 91.5 g/cm^2).

For this test, the following three suspensions were used:

Suspension A: Top one-fifth of supernatant after 10-minute settling of a bentonite suspension, coagulated with 20 mg/l alum. (pH 7.0, Solid Conc. 2.7 mg/l).

Suspension B: The same as A except the floc suspension was aged for three days before the measurement of silting index.

Suspension C: Untreated bentonite suspension (pH 7.0, Solid Conc. 2.0 mg/l).

To each suspension seven filtration pressures ranging from 92 g/cm^2 to 3,770 g/cm^2 were applied. From the plot of $\frac{t}{V}$ vs V the specific resistance at each pressure was determined. The change of specific resistance with pressure can be attributed to the compressibility of the floc-cake, and the compressibility can be calculated from the following equation as used by Coackley (Reference 18):

$$R_s = R_o P^s \qquad (15)$$

R_s = specific resistance at certain pressure (cm/g)

R_o = specific resistance if the solid is absolutely rigid (cm/g)

P = pressure (g/cm^2)

S = compressibility

The results are shown in Figure II-3 and the following can be calculated from the figure.

TABLE II-1

COMPRESSIBILITY OF FILTER CAKE

Suspension	A	B	C
Type of Solids	Fresh Floc	Aged Floc	Bentonite
S: Compressibility	0.506	0.347	0.250
R_o: Intrinsic Specific Resistance (cm/g)	0.796×10^{12}	4.95×10^{12}	6.95×10^{12}

The compressibility of fresh floc is the greatest and it decreased with aging. Bentonite clay also showed considerable compression. Coackley (Reference 18) reported that the compressibility of activated sludge ranged from 0.60 to 0.80 while the same for digested sludge ranged from 0.70 to 0.86.

The great variation of specific resistance with pressure indicates the necessity of using a standard pressure if the results are to be compared. The effect of aging on the specific resistance was significant and need for immediate measurement of freshly collected sample is indicated.

Effect of pH and Alum Dosages on Specific Resistance

In order to observe the floc quality reflected as the specific resistance,

alum floc produced at various pH were used in the measurement of the specific resistance. The following were the test conditions:

Suspension: Suspended solid - 50 mg/l bentonite
Alkalinity - 50 mg/l as $CaCO_3$

Alum Dosage - 20 and 60 mg/l as $Al_2 (SO_4)_3 \cdot 14.3 H_2O$

pH: 5.0 - 9.0

Jar test: Sample volume - 500 ml
Mixing = 15 minutes at 40 RPM
Settling - 10 minutes

Specific Resistance Measurement: Pressure - 20 psig
Filter - 0.45μ M.F.

From the results shown in Figure II-4 the following may be concluded:

1. Specific resistance (i.e., the inverse of specific permeability) is lower at lower pH values. In other words, floc produced at low pH is more rigid than the floc produced at pH 7.0.

2. The variation of specific resistance has no apparent relationship with the degree of clarification. The basic assumption in the use of permeability data to express the floc strength is that the rigidity of floc structure is the same as the strength of floc. The ability of floc to withstand shearing stress may not exactly correspond to the floc rigidity. In the following section, another approach of measuring the strength was investigated.

INCREMENTAL TURBIDITY METHOD

The settling velocity of a floc is assumed to follow Stoke's law and is thus proportional to the square of particle diameter. Therefore, a floc which is fragmented by the application of a high shear stress should have the lower settling velocity than the original floc, provided they have the same density. This settling velocity can be measured directly or indirectly.

The measurement of supernatant turbidity after a fixed time of settling is the indirect method of measuring the settling velocity of original or fragmented flocs. The stronger flocs will exhibit less fragmentation on exposure to a given shear stress than the weaker flocs. Consequently, the former will show the lower value of supernatant turbidity if both floc suspensions had the same turbidity at the beginning.

Procedure

1. Floc suspension (500 ml) produced by the pretreatment process of a water plant or by jar test coagulation is collected.

2. The suspension is passed through a capillary tube by gravity and collected into a 600 ml beaker. Flocs are broken down by the shear force occurring in the tube. The method of shear stress calculation is described

in Appendix A.

3. Settle the suspension for 15 minutes. Collect 25 ml of supernatant by pipeting out from 2.0 cm below the surface. The subsurface collection of the supernatant sample was necessary because a significant portion of floc floated on the surface due to surface tension.

4. Do the same as step 3 with unfragmented floc suspension.

$$\Delta B = \frac{B_2 - B_1}{B_1} \times 100 \qquad (16)$$

B_1 = turbidity of unsheared floc suspension

B_2 = turbidity of sheared floc suspension

ΔB = percent increment of turbidity

The main difficulty with this method was the poor reproducibility. On a given floc suspension, the reproducibility was 53 percent in terms of the coefficient of variation. (When the increment was not divided by B_1, the coefficient of variation was 15.2 percent.) In another floc suspension, the coefficient of variation of the percent increment was 132 percent. The variation of reproducibility with the type of floc suspension may be explained as follows:

Considering two hypothetical cases of the measurement as shown in Figure II-5, Suspension A gives samples of fragmented and unfragmented floc, both at the plateau region of the settling curve and the reproducibility is relatively good. On the other hand suspension B gave one sample at the sloping region while the other sample is at the plateau region. Therefore, a small error in time of sampling or the depth of sampling may result in a significant error in the resulting turbidity of the sample.

Another difficulty with this method is the need to normalize the increment of the turbidity by dividing with the initial supernatant turbidity as shown in equation 16. This was necessary in order to obtain the same value of percent increment of turbidity when two different floc concentrations of identical floc strength are to be compared. Usually the supernatant turbidity of unfragmented flocs is very small and difficult to measure exactly. Therefore a slight error in the measurement of the turbidity results in a significant variation in the calculated value of percent increment of the turbidity. Therefore, the following method was investigated to overcome the difficulties of this method.

MEASUREMENT OF FRAGMENTED FLOC SIZE

Flocs were fragmented under a certain high average shear stress and the settling velocity was directly measured rather than using the indirect method cited above. The velocity of settling was converted to a size

distribution of the floc suspension and median size was selected to represent a group of fragmented floc. If the original floc was strongly bonded, the median size of the fragmented floc was greater than the median size from a weaker floc. Therefore, the size of fragmented floc serves to indicate the floc strength.

Apparatus

The shearing of floc was made by the use of a slanted capillary tube. This selection was made because there is a well defined theory to calculate shear stress in pipe flow, and because of the ease of adjustment of the mean shear stress by changing the slope of the tube. The device used is shown in Figure II-6. After the floc was fragmented, the measurement of settling velocity can be measured by placing a photometer at a certain depth and recording the decrease of turbidity with time. The measurement of turbidity is usually made by the light transmission method. However, the light transmission method is not sensitive to turbidities of less than 2.0 ppm, and the Jackson unit light scattering method (nephelometry) was adapted to our study. Our nephelometer for the measurement of settling rate consisted of a settling cell, a box to collimate the incident light, a photocell, and a sensitive current meter (Hach Turbidimeter). The sketch of the settling cell is shown in Figure II-6. The dimensions of the cell are 2"x2"x2.5" and a narrow beam of light (1.0 mm thick) illuminates the suspension at 3.0 cm depth. The following modifications may be worth noting:

1. The slanting of sample cell. One significant problem in this measurement was the tendency of floc to adhere to the walls of the sample cell which reduces the intensity of incident and scattered light. To overcome this problem, the entire device was slightly tilted. This prevented adhesion of floc to cell walls facing incident light source and the scattered light passage to the photoelectric cell. The slanting angle was 2.5°.

2. Calibration of the nephelometer. The light intensity received by the photoelectric cell was calibrated in Jackson Turbidity Units, using kaolinite suspensions. This scattering procedure enabled us to avoid the complex problem of light path obstruction by particles in suspension.

3. Mixing of floc suspension. A critical part of this approach is the mixing of the sheared or non-sheared floc to achieve initially homogeneous suspensions. Any amount of mixing will affect the flocculation kinetics. Paddle mixing of sheared flocs increased the floc size; this phenomena was obvious even to the naked eye. It appears that the addition of clear water gives good and continuous mixing without any noticeable increase of floc size. In order to maintain constant ionic conditions, the filtrate of floc suspension was added to the suspension while the sheared flocs were flowing out from a capillary tube. The result shown in Figure II-7 partly supports the assumption that mixing by dilution does not significantly alter the floc size to an extent which will overshadow the effect of shearing forces exerted in the capillary tube.

Procedure

A 500 ml sample of floc suspension is collected into a beaker. The sample beaker is connected to the capillary tube and gravity flow begins,

and the original floc suspension is kept mixing at 20 RPM to prevent settling. When the sample collected in the settling cell reaches 100 ml, the flow is stopped. To the 100 ml sample, 50 ml of the prepared filtrate (no floc) of the same suspension is added. The addition of 50 ml filtrate resuspends small fractions of floc settled at the bottom and uniform suspension could be obtained. Paddle mixing inside the sample cell was avoided because it caused re-agglomeration of fragmented floc. Immediately after the addition of filtrate, time measurement begins. The sample cell is covered and put into the nephelometry device, and the change of turbidity reading with time is noted. From these data, turbidity versus time is plotted and the turbidity at time zero is found by extrapolation. Each measurement of time is converted to corresponding Stoke's size as shown in Appendix B, and Stoke's size versus percent undersize is plotted on log-probability paper.

Application of the Photometric Method

A floc suspension was prepared with alum and raw water from San Pablo Reservoir. Two different magnitudes of mean shearing forces were exerted on the floc. The first at 12.2 dyne/cm^2 and the second at 27.3 dyne/cm^2. As shown in Figure II-7, the size distributions of the two sheared and one unsheared floc suspensions were quite different. The log-probability plots of log-normal size distributions were not straight lines as might be expected from log-normal size distributions. Curve C showed an asymtotic bend at the upper left, and curve B showed an "S" shape (the dotted line is based on what is considered to be unreliable data). The slight variation is exaggerated by the log-probability plot.

According to Irani (Reference 19) the shape of curve C indicates the limited growth condition of the floc in which the largest particle is some finite size, not infinite. The "S" shape of curve B seems to indicate the presence of two populations mixed in some proportion. Since the floc passes through a capillary tube the upper limit of floc size cannot be greater than the diameter of the capillary. Probably, the maximum size was governed by the shearing forces exerted. It may be said that the results shown in Figure II-7 support the limiting-size theory.

Reproducibility of Size Measurement

The poor reproducibility of the incremental turbidity method directed our interest to the photometric method. On water from San Pablo Reservoir 30 ppm alum was added and the floc produced was sheared at 12.2 dyne/cm^2. The nine measurements are plotted on log-probability paper which showed "S" shaped curves. The reproducibility varied depending on the percent undersize selected and the coefficients of variation calculated are shown in Table II-2. The best reproducibility could be observed at 60 percent undersize. The coefficient of variation was 6.8 percent, which is appreciably better than that obtained by the incremental turbidity method.

TABLE II-2

REPRODUCIBILITY OF PARTICLE SIZE MEASUREMENT BY PHOTOMETRY
(From nine measurements)

% Undersize	Average Size (Micron)*	Coeff. of Variation (%)
20	69.2	15.5
30	111.2	10.3
50	180.0	6.8
60	206.0	6.1
70	228.5	9.2
90	302.5	16.7

*at floc density of 1.006 g/cm^3.

Measurement of Floc Density

In order to calculate floc sizes with reasonable accuracy from its subsidence rate, it is necessary to know the floc density. However, such information is very scarce and unreliable. Ives (Reference 20) calculated the density of iron floc to be 1.0068 while Fair & Gayer (Reference 21) reported the minimum density of alum floc to be 1.002. The density of floc which is composed of clay particles and alum hydrolysis species may depend upon pH, alum dosage, content of clay, etc.

Several methods of density measurement were evaluated and the use of sucrose to increase the liquid density was considered to be most applicable. Sucrose (cane sugar) solution is non-ionic, and would not affect ionic environment of floc as much as ionic solutions. It is possible to calculate the floc density by measuring the decrease of subsidence rate when sucrose was added to the floc suspensions as follows:

Subsidence rate without addition of sugar.

$$V_1 = \frac{l}{t_1} = \frac{g}{18} \frac{d^2}{\eta_1} (\rho_f - \rho_1) \qquad (17)$$

Subsidence rate with the addition of sugar.

$$V_2 = \frac{l}{t_2} \frac{g}{18} \frac{d^2}{\eta} (\rho_f - \rho_2) \qquad (18)$$

V_1, V_2 = settling rate in water and sugar solution

l = depth of settling

t_1, t_2 = time of settling in water and sugar solution

g = gravity const.

ρ_1, ρ_2 = density of water and sugar solution

ρ_f = density of floc

d = equivalent Stoke's diameter

Because the size of floc in equation (17) and (18) is the same, it follows:

$$\frac{\rho_f - \rho_2}{\rho_f - \rho_1} = \frac{t_1 \eta^2}{t_2 \eta_1} \qquad (19)$$

In equation (19) the only unknown is ρ_f; t_1, and t_2 of median size can be found from the plot of $1/\sqrt{t}$ vs undersize % on log-probability paper.

A water sample from a local reservoir was coagulated at alum dosage of 10, 20, 30, and 40 mg/1. The resulting floc was fragmented at the shear stress of 12.15 dyne/cm^2. The subsidence rate was measured with original media and with sugar added (0.83 percent). The result of the density measurement is shown in Table II-3.

TABLE II-3

DENSITY OF ALUM FLOC

Alum Dosage	Density g/cm^3
10 mg/1*	---
20 mg/1	1.0067
30 "	1.0054
40 "	1.0060
Average =	1.0060

*No measurement could be made because the settling rate of the floc was extremely slow.

It appears that the variation of density with alum dosage is not significant. The average density of 1.006 is very close to the value reported by Ives (Reference 20). However, this density value may still vary with the type of coagulant, pH, and the type and concentration of suspended solids. In our study, we would be using the same type and concentration of suspended solids, and the same type of coagulant (alum) throughout the experiment. Therefore, the calculation of median floc size based on the floc density of 1.006 may serve the purpose.

Effect of Shearing Stress on the Breakdown of Floc

Various magnitudes of shear stress ranging from zero the 27.30 dyne/cm^2 were applied to alum floc. The results are shown in Figure II-8 and the

following conclusions are drawn.

1. We can define a threshold shear force as an amount of shear above which no significant increase of the breakdown of floc could be observed. The result in Figure II-8 shows that there is a distinct threshold shear force at 20 percent size but it was not so apparent at 50 percent and 90 percent size.

2. As the shear force increases the spread of size distribution decreases, i.e., the particle size becomes more uniform.

Effect of pH on the Median Size of Fragmented Floc

The strength of floc (expressed as the median size of the fragmented floc) was measured as a function of pH. The same water tested in the measurement of specific resistance shown in Figure II-4 was used. Two alum dosages of 20 and 60 mg/l were applied.

The afore-cited procedure and calculations were made, and the results are shown in Figure II-9. The results show the following:

1. There is a pH which gives maximum floc strength for a given alum dosage.

2. The pH for maximum floc strength does not always occur at the pH of maximum clarification. At 20.0 mg/l alum dosage, the pH range of good floc formation and clarification was from 4.0 to 7.5 while the maximum floc strength occurs at pH 6.2.

Comparison of the Two Methods of Floc Strength Measurement

For the results shown in Figures II-4 and II-9 the experimental conditions of coagulation were the same, but the methods of floc strength measurement utilized were different. In the former case the specific resistance of filter cake was used as an index, while in the latter case the median size of fragmented floc after application of shear stress was used as an index of floc strength. The assumption in the specific resistance (or permeability) method is that the stronger floc will maintain its shape and porosity (i.e. stiffness) during filtration much better than weaker floc. The assumption in the latter method is that stronger floc can resist shearing stress better than weaker floc and therefore that median fragmented size of the stronger floc will be bigger than that of the weaker floc.

The discrepancy between the results shown in Figures II-4 and II-9 may indicate either that the stiffness of floc measured by the specific resistance (or permeability) method is not the same as the toughness of floc to resist shear stress measured by the median floc size method, or that the specific resistance method is not really measuring the stiffness of floc.

Considering the definition of floc strength, the shearing method is probably more appropriate in the study of floc strength in relation to the depth filtration process.

Inherent Errors in the Shearing Method

The method does not give true particle size distributions because of the following inherent errors:

1. The variation of the light extinction coefficient with particle sizes is neglected.

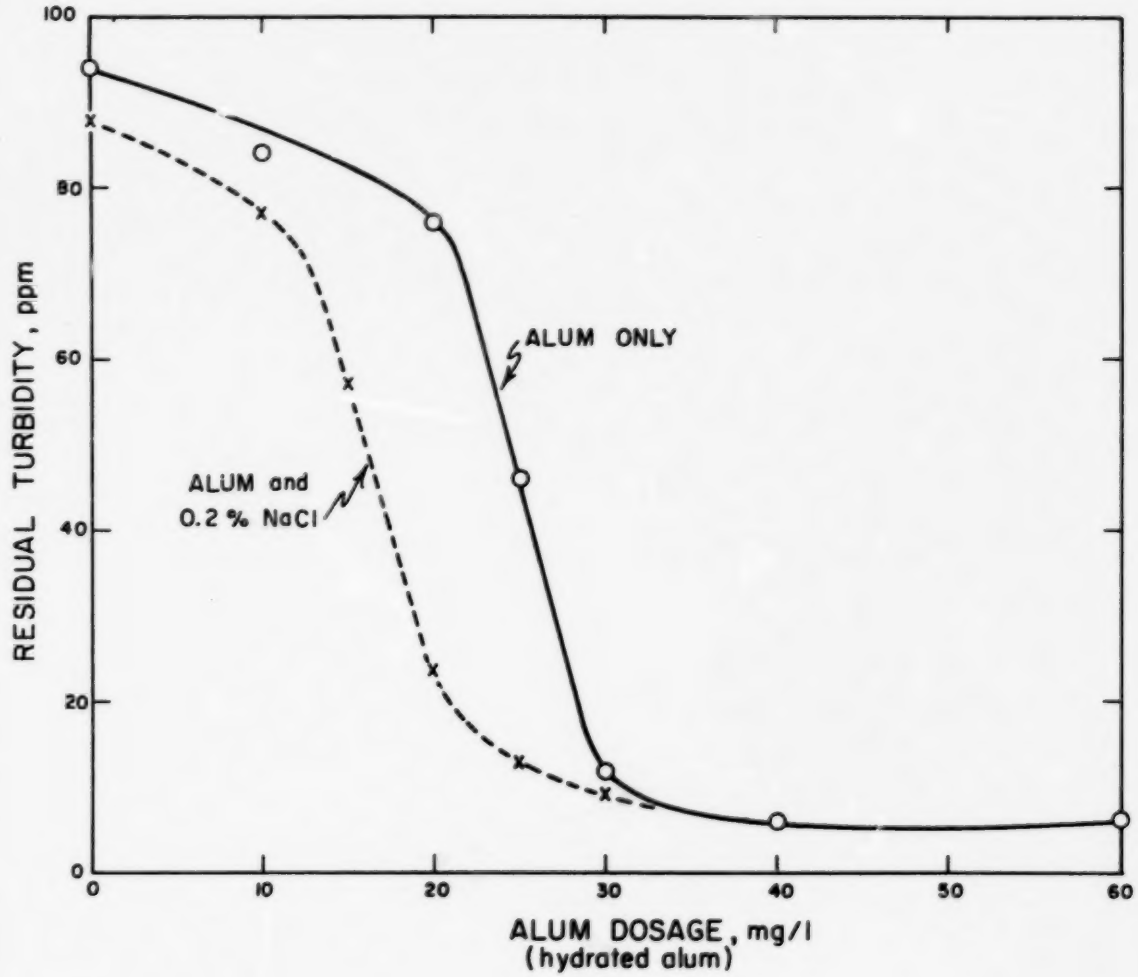
2. The particles are assumed to be spherical in the Stoke's law calculation.

3. The density of flocs may change with physical and chemical conditions. Since little data are available on this aspect, a constant value had to be used in the floc size calculation.

However, this method may serve the purpose of comparative measurement of floc strength in this study.

FIGURE II-1

EFFECT OF 0.2 % NaCl ON THE COAGULATION OF LOCAL RUNOFF WATER



RAW WATER: COLLECTED AT SAN PABLO FILTER PLANT ON 23 FEB 1967

FIGURE II-2

SKETCH OF SILTING INDEX APPARATUS
(Side View)

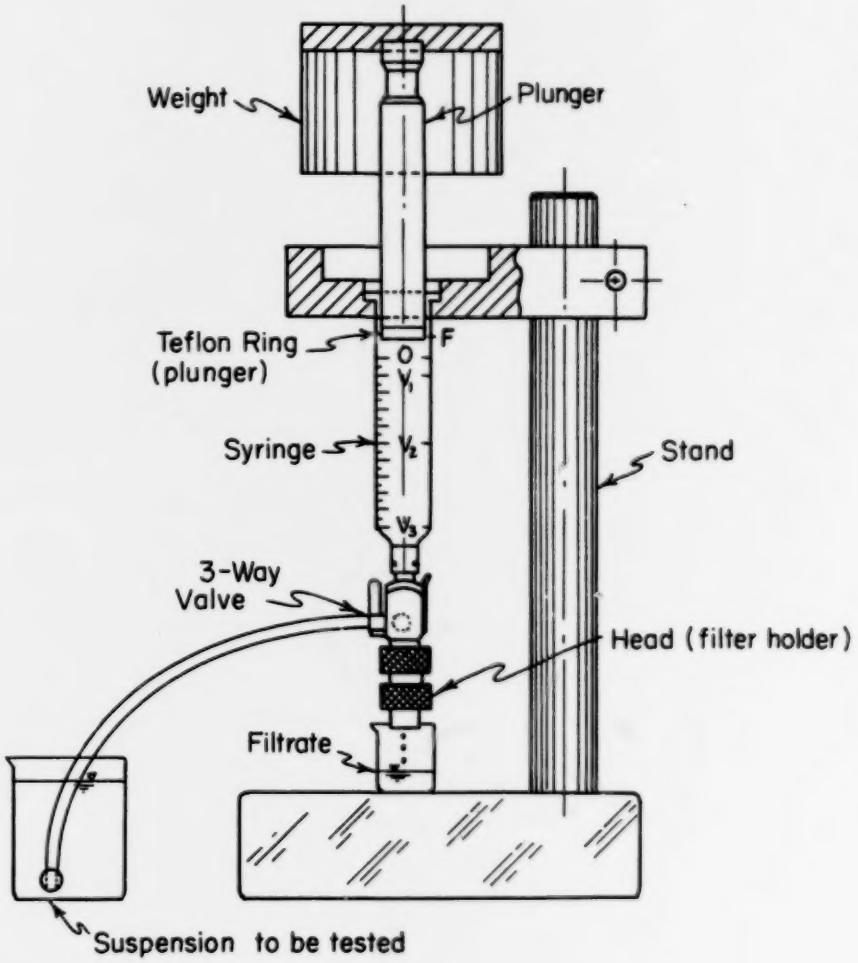


FIGURE II-3

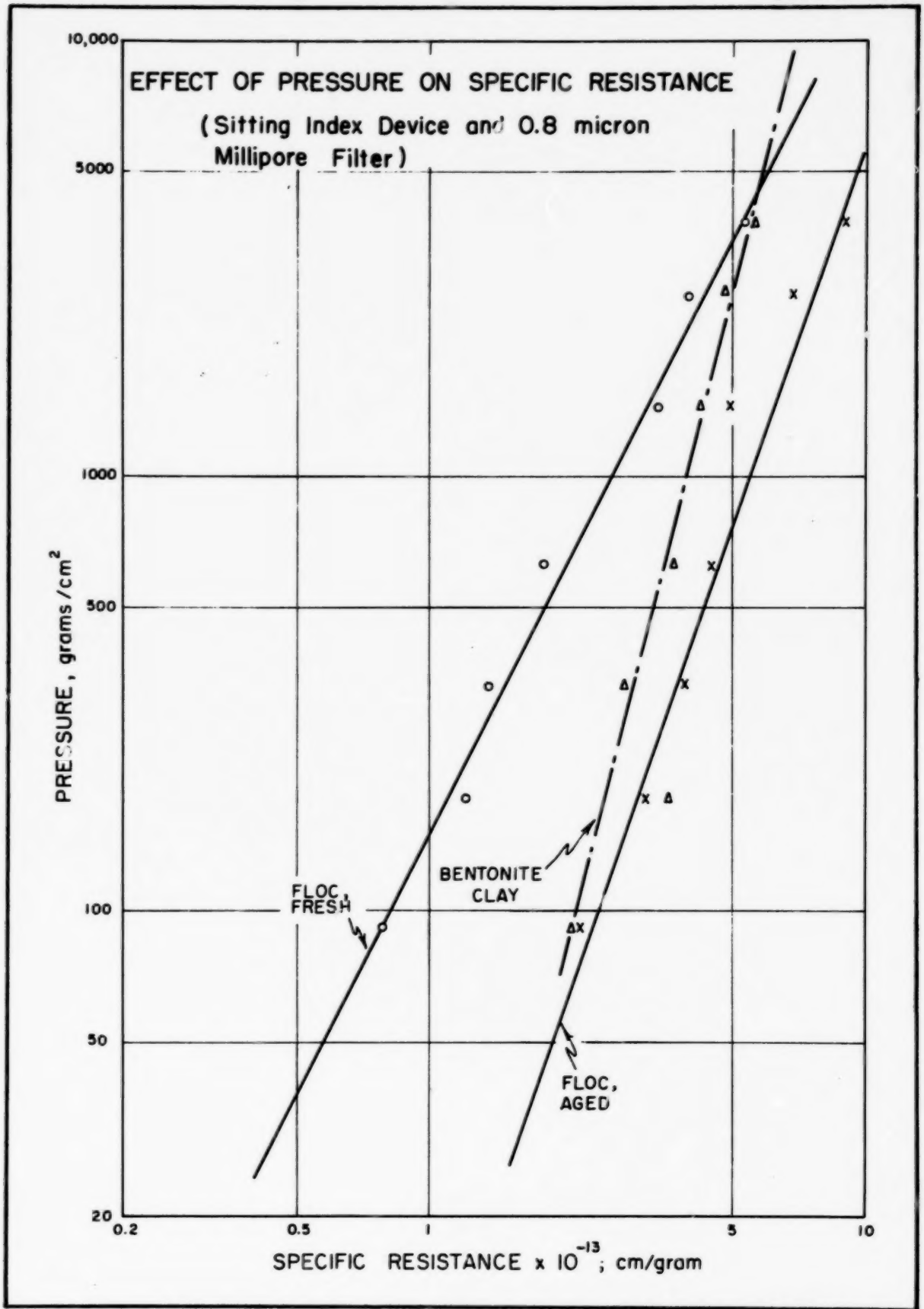
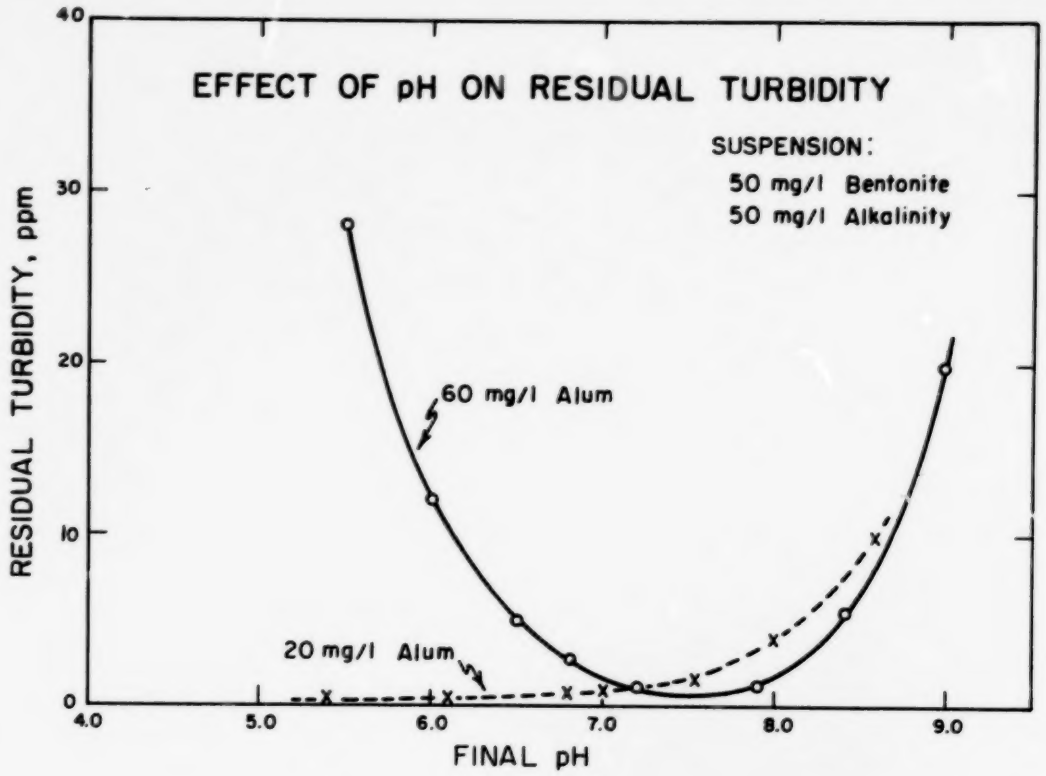
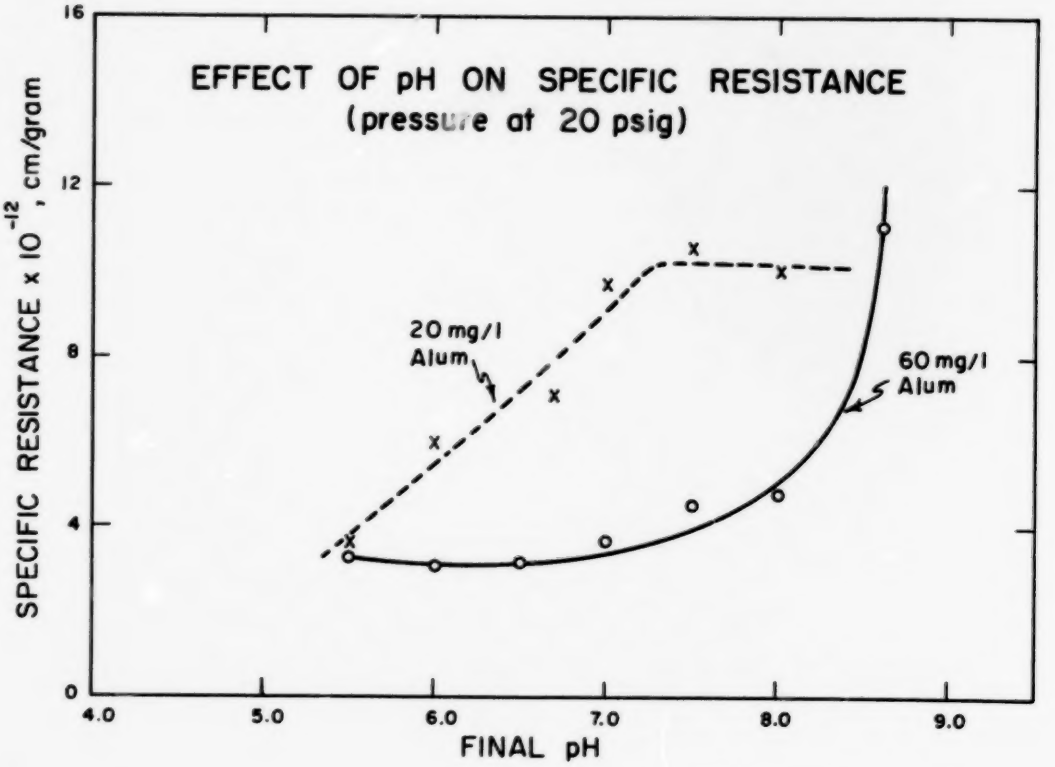
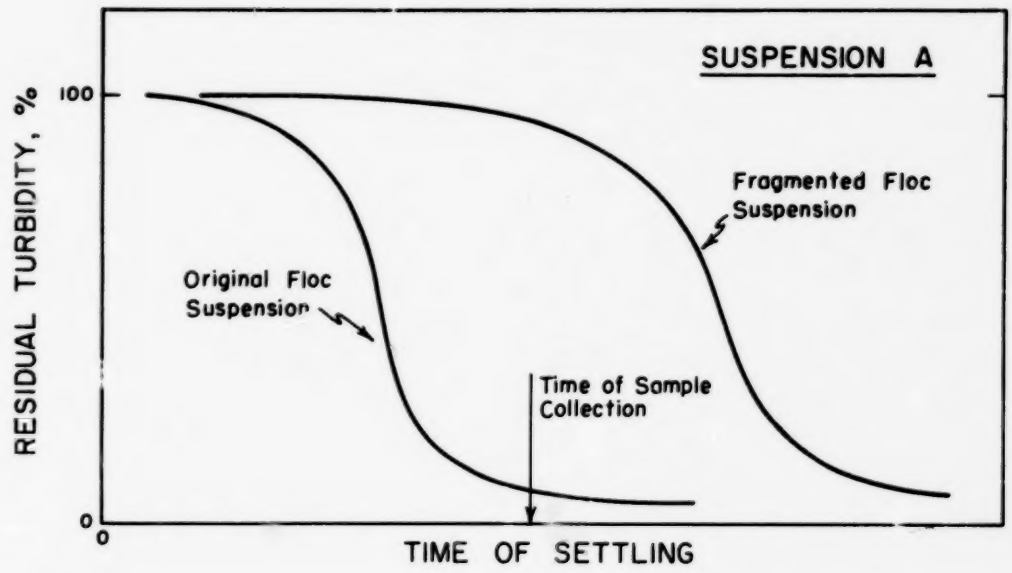

EFFECT OF PRESSURE ON SPECIFIC RESISTANCE
(Sitting Index Device and 0.8 micron Millipore Filter)
PRESSURE, grams/cm²
10,000
5000
1000
500
100
50
20
0.2
0.5
1
5
10
SPECIFIC RESISTANCE x 10⁻¹³; cm/gram
FLOC, FRESH
BENTONITE CLAY
FLOC, AGED

FIGURE II-4


EFFECT OF pH ON RESIDUAL TURBIDITY
SUSPENSION:
50 mg/l Bentonite
50 mg/l Alkalinity
RESIDUAL TURBIDITY, ppm
60 mg/l Alum
20 mg/l Alum
FINAL pH
40
30
20
10
0
4.0
5.0
6.0
7.0
8.0
9.0


EFFECT OF pH ON SPECIFIC RESISTANCE
(pressure at 20 psig)
SPECIFIC RESISTANCE x 10⁻¹², cm/gram
20 mg/l Alum
60 mg/l Alum
FINAL pH
16
12
8
4
0
4.0
5.0
6.0
7.0
8.0
9.0

SETTLING CHARACTERISTICS OF SUSPENSIONS AFFECTING REPRODUCIBILITY OF INCREMENTAL TURBIDITY



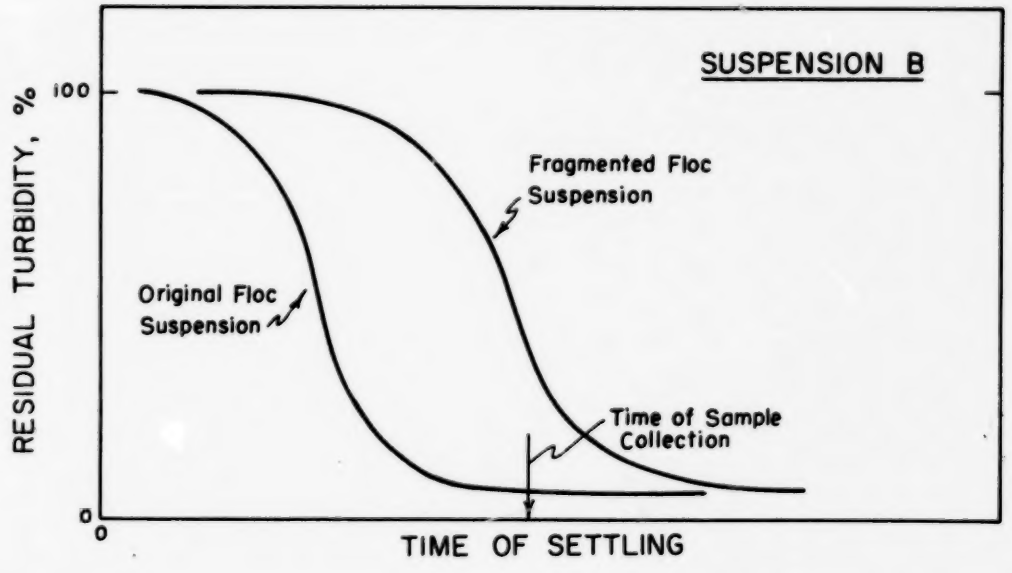


FIGURE II-6

SKETCH OF FLOC SHEARING DEVICE AND SETTLING CELL

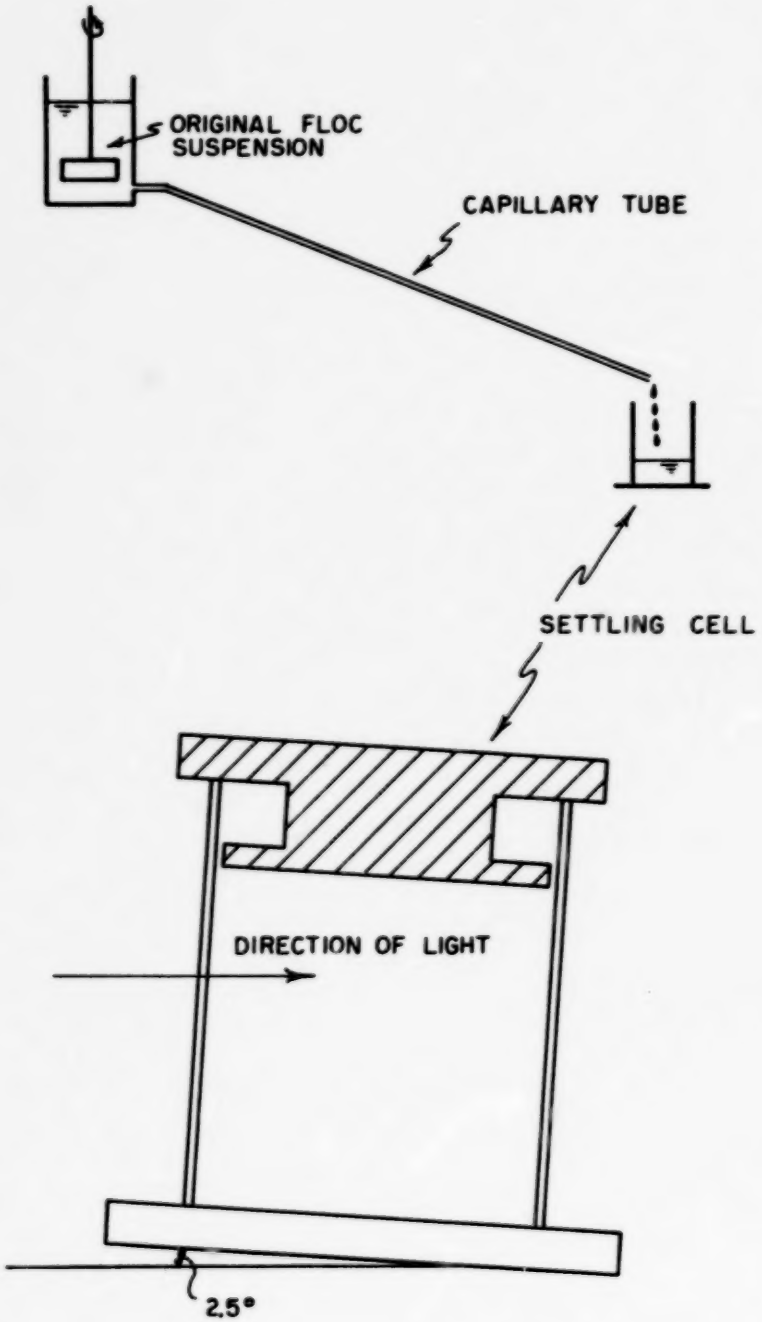
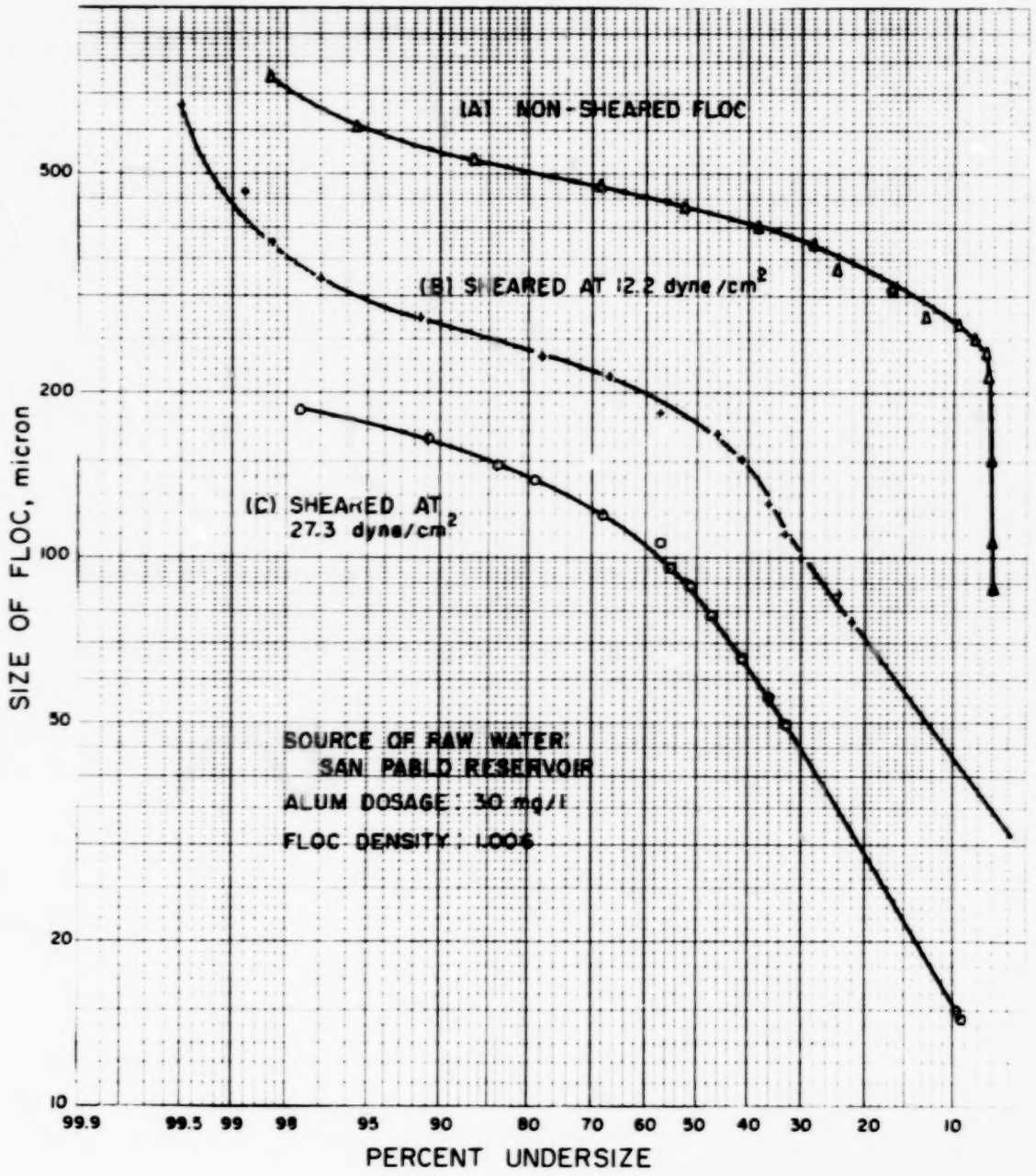


FIGURE II-7

EFFECT OF SHEAR STRESS ON FLOC PARTICLE SIZE DISTRIBUTION



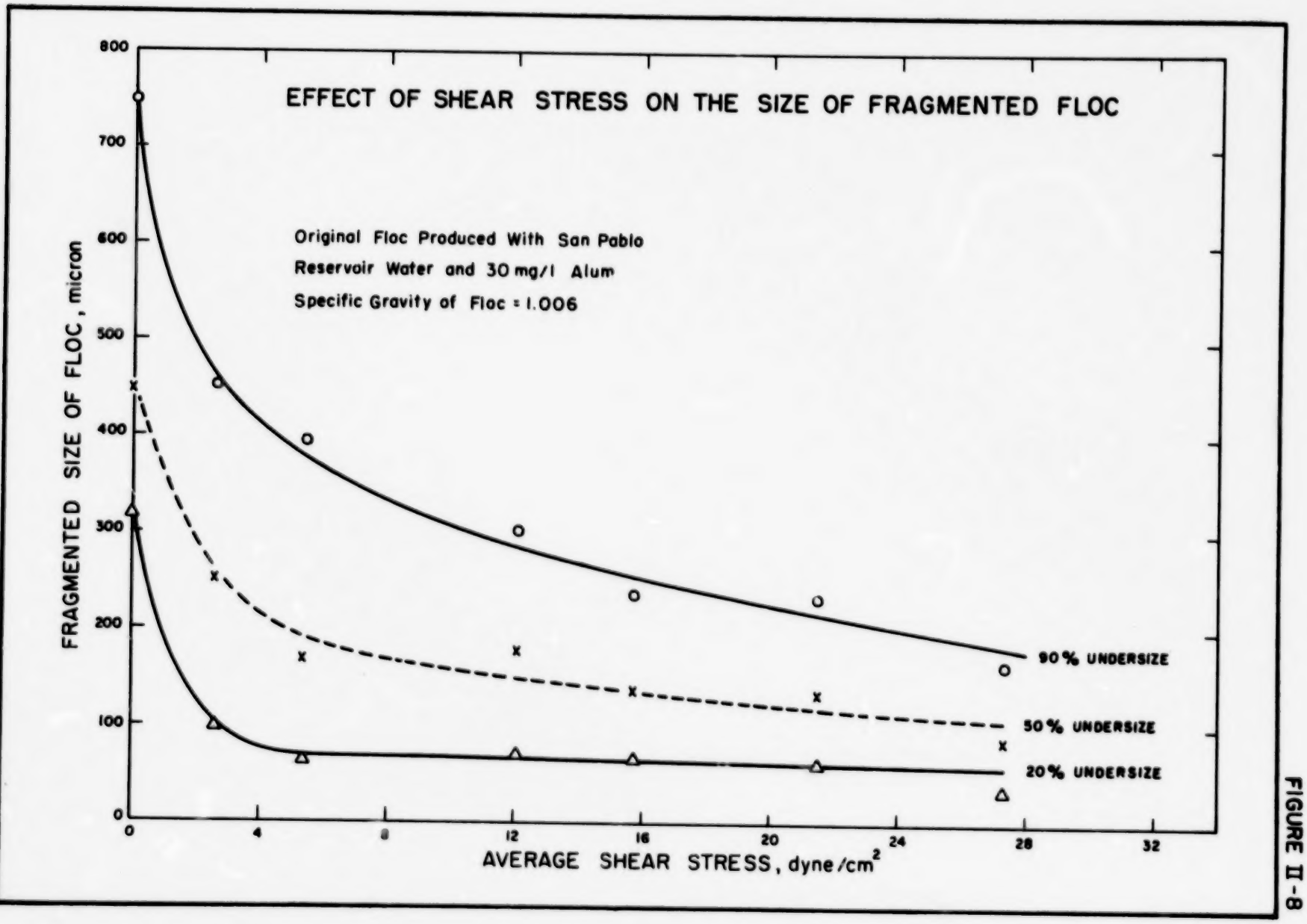
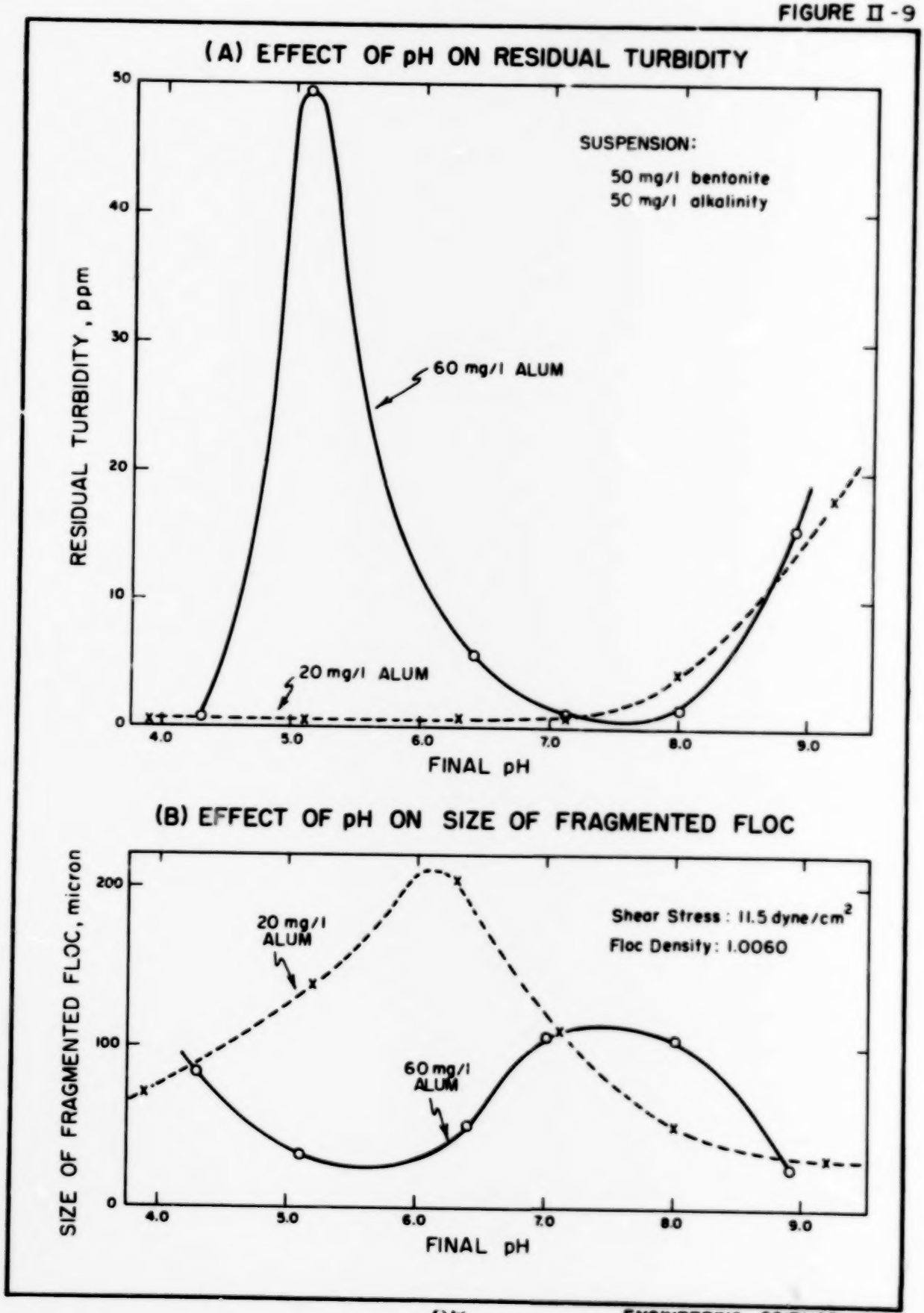

EFFECT OF SHEAR STRESS ON THE SIZE OF FRAGMENTED FLOC
Original Floc Produced With San Pablo
Reservoir Water and 30 mg/l Alum
Specific Gravity of Floc = 1.006
FRAGMENTED SIZE OF FLOC, micron
AVERAGE SHEAR STRESS, dyne/cm²
90% UNDERSIZE
50% UNDERSIZE
20% UNDERSIZE
0
100
200
300
400
500
600
700
800
4
8
12
16
20
24
28
32

FIGURE II-8

FIGURE II-9


(A) EFFECT OF pH ON RESIDUAL TURBIDITY
SUSPENSION:
50 mg/l bentonite
50 mg/l alkalinity
60 mg/l ALUM
20 mg/l ALUM
RESIDUAL TURBIDITY, ppm
FINAL pH
(B) EFFECT OF pH ON SIZE OF FRAGMENTED FLOC
20 mg/l ALUM
60 mg/l ALUM
Shear Stress: 11.5 dyne/cm²
Floc Density: 1.0060
SIZE OF FRAGMENTED FLOC, micron
FINAL pH

CHAPTER III

MEASUREMENT OF FILTERABILITY

The determination of filterability of pretreated water has been of continuing interest since early 1940. However, the difficulties of evaluating all related parameters left this determination still unresolved. There are two main approaches to the problem, one based on the theory of filtration, and the other is an empirical approach.

In order to find a rational approach to the measurement of filterability, it is imperative to investigate the theory of filtration. The general theory of filtration advanced by Hermans and Bredee (Reference 22) and Grace (Reference 23) will be discussed first, and two modern theories of depth filtration will then be considered.

FILTRATION LAWS AND MECHANISMS OF PORE PLUGGING

Hermans and Bredee (Reference 22) analyzed an entire spectrum of filtration and proposed a series of filtration laws which depend on the hypothetical mechanism of pore plugging. These laws were derived on the assumption that there are four mechanisms of pore plugging. They are; a) complete blocking, b) standard blocking, c) intermediate blocking, and d) cake filtration. The physical picture of each filtration mechanism and the corresponding equations are shown in Figures III-1 and III-2. These derived equations stem from a common differential equation which can be adapted to any phase of a filtration cycle by adjusting two constants (n and K) as follows:

For constant pressure filtration:

$$\frac{d^2t}{dv^2} = K\left(\frac{dt}{dv}\right)^n \qquad (20)$$

For constant rate filtration:

$$\frac{d(\Delta p)}{dv} = K(\Delta p)^n \qquad (21)$$

n = a constant defining the mode of filtration as shown in Figure III-1.

n = 2 for complete blocking

$n = \frac{3}{2}$ for standard blocking

n = 1 for intermediate blocking

n = 0 for cake filtration

k = a constant which is a function of filter medium characteristics and the manner of filter operation

v = volume of filtration

t = time of filtration

Δp = pressure drop

Equation (21) states, in simple terms, that the rate of change of the filtration resistance is proportional to the instantaneous filtration resistance raised to a power. The power or exponent is dependent on the mode of filtration.

Cake filtration is the mode of filtration in which the retained material itself act as filter medium. In standard blocking filtration the suspended solids are removed by retention by the solid on the wall of pore space, gradually reducing the diameter of the pores. This type of filtration is most common in rapid sand filtration and is called depth filtration. Complete blocking filtration occurs when a capillary pore is completely sealed as a solid tries to pass it. When a filtration cycle begins, the initial mode of filtration will be either complete blocking or standard blocking depending on the relative size of solids to the pore size of a filter. As filtration progresses, the mode of filtration shifts from standard blocking to intermediate blocking and finally to cake filtration. The physical picture of intermediate blocking is not clear yet.

MODERN THEORIES OF DEPTH FILTRATION

In the filtration process for potable water production, deep sand beds of relative coarse grain size (compared to filter cloths) are used and consequently the predominant mode of filtration in the sand bed is standard blocking. The various stages of intermediate blocking or cake filtration also occur, depending on the floc size, the characteristics of filter medium, and the rate of filtration. In the operation of a rapid sand filter it is desirable to have a low increase of headloss. Cake filtration and intermediate blocking leads to a rapid increase of headloss and they are not desirable. The ideal filtration process requires the maintenance of standard blocking filtration with the production of relatively clean effluent. The filtration equations shown in Figure III-1 for the standard blocking filtration are not adequate to express filtration phenomena of depth filtration because they do not include all the variables such as grain size, filtration rate, floc strength, etc.

Several investigators have proposed theories describing depth filtration which are based on the assumption that the filtration cycle of a deep bed is terminated before the onset of the cake filtration stage. There are two schools of thought regarding the mechanism of floc removal in a sand bed. The first group assumes that the loss of filtration efficiency with time is due to the change of geometrical structure of pore spaces. Another group proposes that this phenomenon is due to the dynamic changes in filtration conditions and considers the strength of sediment (or floc) to be of primary importance.

Ives (Reference 24) belongs to the first group. His equation for the depth filtration can be written as follows:

$$\frac{\partial C^*}{\partial x} = \left(a_1 + a_2\sigma - \frac{a_3 q^{*2}}{m_o - q^*}\right) C^* + \frac{a_4 q^* (1 - m_o)^{1/3}}{(m_o - q^*)(1 - m_o + q)^{1/3}} \qquad (22)$$

C^* = floc concentration, cm^3/cm^3

a_1 = initial filter coefficient

a_2 = constant describing initial increase of filter coefficient

a_3 = constant describing decrease of filter coefficient

a_4 = constant describing the effect of floc strength

q^* = volume of deposit per unit volume of filter

m_o = initial porosity of a filter

In equation (22) constant a_1, a_2, and a_3 are also functions of filtration rate, grain size and viscosity. Ives tested the applicability of equation (22) on the filtration of relatively heavy and discrete particles through a homogeneous filter media. The last term in equation (22) describing the effect of floc strength, therefore, was not investigated. Due to the several assumptions made for the deviation of the equation, the engineering application is not considered practical.

The second group may be represented by Mintz (Reference 25) et al. Mintz presented the following equations:

$$-\frac{\partial C}{\partial x} = \frac{\beta}{V^{0.7} d^{1.7}} C - \frac{\beta}{V^{0.7} d^{1.7}} \frac{q}{q_o} C_o \qquad (23)$$

$$t_1 = \frac{1}{K} \frac{q_o}{VC_o} \left(x - \frac{V^{0.7} d^{1.7}}{\beta} x_o\right) \qquad (24)$$

$$t_2 = (H_{lim} - H_o) \left[\left(\frac{d_m}{d_{20}}\right)^2 i_o F(\sigma_o) \frac{VC_o}{q_o}\right]^{-1} \qquad (25)$$

C = gravimetric concentration of suspended solids, mg/l

x = distance in filter from inlet surface

β = empirical constant

V = rate of filtration

d = grain size of filter medium

q = gravimetric quantity of deposit per unit volume of filter bed, mg/l

q_o = maximum attainable deposit, mg/l

C_o = concentration of suspension of filter influent

t_1 = time of protective action (time of floc breakthrough)

t_2 = time to reach a limiting headloss

K = constant, function of the degree of clarification desired

X_o = constant, function of the degree of clarification desired

H_{lim} = maximum total headloss

H_o = initial total headloss

d_m = mean grain size of non-uniform filter bed

d_{20} = mean grain size of top 20 percent layer

i_o = hydraulic gradient

σ_o = maximum degree of pore saturation, volume of deposit per unit pore space

$F(\sigma_o)$ = function of σ_o

Mintz has prepared a table to express X_o, k, and $F(\sigma_o)$. His recommendation for the optimum design of a filter is to adjust parameters so that t_1 equals t_2. He emphasized the importance of floc strength. In order to apply equations (23), (24), and (25), parameters such as β, q_o, and σ_o need to be determined and these three parameters are all functions of floc strength.

METHODS OF FILTERABILITY MEASUREMENT INVESTIGATED BY OTHERS

The term "filterability" is considered to represent the ease of filtration of a certain suspension under given conditions of filtration. There are three factors which determine the filtration conditions:

1. The characteristics of floc in a suspension
2. The manner of filter operation (e.g. direction of flow and rate of filtration)
3. The characteristics of the filter media

It is impossible to evaluate all three factors at once in a filtration process. To evaluate one of the above factors, the other two have to be fixed. For evaluating the effect of floc strength on the filterability, the filtration rate and the filter media must be constant.

Several methods of measuring filterability of raw or pretreated water are proposed in the following paragraphs.

Measurement of Filtrate Volume

According to Boucher (Reference 26), the word "filterability" was first used by A. Houston. He proposed to express filterability by measuring the volume of filtrate obtained in one minute. The filter used was a linen cloth through which 100 ml of the suspension had been previously filtered.

Measurement of Headloss Increase

Greenshield (Reference 26) measured the headloss at the beginning and the end of a filtration cycle and the ratio of headloss is taken to represent filterability. He used a sintered glass filter and the duration and the rate of filtration were fixed.

Filterability Index

Boucher's (Reference 26) filterability index was originally developed for the operation of microstrainers. He used the "compound interest law" for the headloss increase across a filter cloth.

$$\frac{dH}{dV} = nH \tag{26}$$

$$H = Ml^{nV} \tag{27}$$

$$LnH = nV + ln^{m} \tag{28}$$

$$\therefore n = \frac{lnH_1 - lnH_o}{V_1 - V_o} = \frac{1}{V_1} \ln H_1/H_o \tag{29}$$

"n" was designated as Filterability Index.

When equation (28) is compared to the equation of intermediate blocking shown in Figure III-1, the similarity is obvious. Therefore Boucher's Index applies only to the stage of filtration where the intermediate blocking is the main mode of filtration. He attempted to apply this index to the rapid sand filtration. However, as Whitehead (Reference 27) and Boucher pointed out, the plot of (lnH) vs "V" does not give straight lines on rapid sand filtration.

SILTING INDEX METHOD

In the afore-cited method of specific resistance measurement for the strength, the product of specific resistance and concentration of floc was

designated as silting index. The silting index is the measure of filterability during the cake filtration stage and is not applicable to the depth filtration in the rapid sand filter.

FILTER PERFORMANCE INDEX

Gamet and Redemacher (Reference 28) proposed water production rate per unit headloss as the index to compare the efficiency of separate filters and termed this the "Filter Performance Index". This parameter may give erroneous results when the floc breakthrough is the limiting factor in the termination of a filtration run because the headloss under such condition is relatively small.

MEASUREMENT OF CONSTANTS IN FILTRATION EQUATION

Ives and Sholji (Reference 29) suggested the determination of the filter coefficients a_1, a_2, and a_3 in equation (22) as measures of filterability. This approach may have the following difficulties.

1. The weakest point in modern filtration theory is the lack of proper methods to measure the specific volume of floc, i.e., the volume of floc deposited in unit volume of filter media (Reference 25). The evaluation of a_1, a_2, and a_3 requires the measurement of the specific floc volume.

2. The effect of floc quality will be neglected if the fourth coefficient, a_4, is not evaluated.

3. The application of these coefficients in the actual design is not practically feasible at the present time.

NEW APPROACH TO THE MEASUREMENT OF FILTERABILITY

Filter Run Index

The importance of floc strength stems in large measure from its effect on filter performance and consequently it is of interest to relate it to some measure of filterability. It is planned to study the performance of four filter media, two representative of sands of traditional sizes and two representing applications of the dual media concept. Floc of various strengths will be applied to these filters and selected measures of performance correlated with these strengths. This section of the report is devoted to developing an appropriate measure of filter performance and indicating its relationship to floc strength.

The efficiency of floc removal can influence filter performance in two ways. The floc should not be so weak as to cause rapid breakthrough. On the other hand, it should not be so strong as to cause a rapid increase of headloss by forming a surface cake. An optimum condition of filter operation, therefore, will be obtained when the breakthrough of floc and the limiting headloss of the filter occur at the same time, as Mintz has suggested (Reference 25). Mintz named the time of floc breakthrough as the time of protective action, t_1. The time to reach a limiting headloss was designated as t_2. According to Hudson (Reference 30), the condition of floc breakthrough

is taken to be the time when the filter effluent shows a turbidity greater than 0.2 ppm. This is based on the observation that most well operated filters produce water with less than 0.1 ppm turbidity. The limiting headloss of a filter is commonly taken to be six feet for 24 inch depth of filter. This criterion is due to the conventional design of water plants.

In the operation of a filter, three conditions can exist, depending on the quality of floc, as shown in Figure III-3.

Case A: $t_1 < t_2$: When the floc is very weak and easily fragmented, the adhesion of floc to the sand is poor and floc breakthrough will occur before the limiting headloss is reached.

Case B: $t_1 > t_2$: When the floc is very strong, it tends to accumulate on top of the filter forming a filter cake. Cake filtration will take place, and the limiting headloss will be reached prior to the time of floc breakthrough.

Case C: $t_1 = t_2$: When the strength of floc is appropriate to the filtration conditions, the time of protective action will coincide with the time of limiting headloss.

From the above reasoning, one can reach the conclusion that the difference of time t_1 and t_2 may indicate how close a filtration condition is from an optimum condition. However, the absolute value of time difference may be affected by the concentration of floc in the filter influent. To reduce this concentration effect, a ratio of time parameters is proposed designated the "filter run index".

$$\text{Filter Run Index} = \frac{t_1 - t_2}{t_1 + t_2} \qquad (30)$$

t_1 = time of protective action

t_2 = time of limiting headloss

The denominator divided by two indicates a value somewhat close to optimum filtration time.

According to equation (30), very weak floc may show a negative value, the very strong floc a positive value and the optimum floc strength the value of zero. Moreover, the greater the sum $t_1 + t_2$, the nearer the index to zero and the better performance.

Method of Measurement

Filterability cannot be determined in small scale bench tests because of its dependency on the character and depth of a filter. In order to measure time t_1 and t_2 a water treatment pilot plant, consisting of pretreatment and

filtration units, is necessary. With this pilot plant, the measurement of the Floc Removal Index can be made as follows:

Case A and C: When the breakthrough of floc occurs ahead, or at the same time, with six feed of headloss, the determination of time t_1 can be made by observing the effluent turbidity from the filter. Time t_2 can be determined by following the headloss gauge until a total of 6 ft headloss is attained.

Case B: When the six ft headloss is reached ahead of the floc breakthrough, it will be very difficult to obtain time t_1 because hydrostatic head much in excess of available head (7 ft to 8 ft) may be necessary to cause floc breakthrough. Also, the necessary duration of filtration may be too long for practical purposes. The following method may be used to determine t_1.

Method of the Floc Breakthrough Time Determination

This method is based on the following assumptions:

1. There is a certain relationship between the total headloss and the penetration of floc.

2. There is a definite relationship between the total headloss and the time of filtration which permits graphical extrapolation.

Regarding the second assumption, there is evidence that the increase of total headloss with time is a relatively linear relationship. Field studies made at local water plants and the data given by Dostal and Robeck (Reference 4) support this.

Hudson (Reference 15) analysis showed:

$$L = k_1 V d^3 h \text{ in laminar flow} \qquad (31)$$

$$L = k_2 V d^2 \sqrt{h} \text{ in turbulent flow} \qquad (32)$$

Stanley's (Reference 16) data was:

$$L = k_3 V^{1.56} d^{2.56} h \qquad (33)$$

The result presented by Davis and Borchardt (Reference 31) may be expressed as:

$$L = k_4 h \qquad (34)$$

L = depth of floc penetration

$k_1 \sim k_4$ = constant, function of flow rate and particle diameter

h = headloss which caused floc penetration

V = filtration rate

d = particle diameter

The equations (31) through (34) can be summarized as follows:

$$L = kh^n$$

$$n = \text{constant}, \quad \frac{1}{2} < n < 1$$

Based on the above two assumptions, the following procedure can be used to find the time of floc breakthrough. The filter should have sampling and manometer ports at several depths from the surface of a filter media.

1. Operate a pilot filter and observe the headloss change with time.

2. Plot time vs. total headloss as shown in Figure III-4(A).

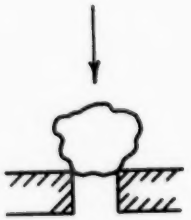
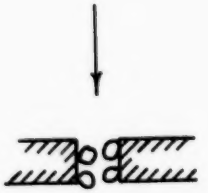
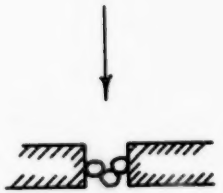
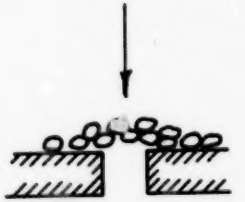
3. Collect samples at each sampling port and determine the condition of floc breakthrough by observing the effluent turbidity. Read the total headloss when the floc breakthrough occurs at a depth of the filter.

4. Plot the depth of headloss against the total headloss on log-log paper as shown in Figure III-4(B).

5. Extrapolate the regression line in Figure III-4(B) and find the total headloss corresponding to the 24 inch of floc penetration.

6. Extrapolate the regression line in Figure III-4(A) and find the time of filtration corresponding to the total headloss found in Step 5.

MODES OF PORE PLUGGING AND FILTRATION EQUATIONS

PHYSICAL PICTURE				
MODE OF FILTRATION	COMPLETE BLOCKING	STANDARD BLOCKING	INTERMEDIATE BLOCKING	CAKE FILTRATION
CONSTANT PRESSURE FILTRATION	$K_1 V = q_o - q$	$\frac{t}{V} = \frac{K_2}{2} t + \frac{1}{q_o}$	$K_3 V = \ln (1 + K_3 t q_o)$	$\frac{t}{V} = \frac{K_4}{2} V + \frac{1}{q_o}$
CONSTANT RATE FILTRATION	$\frac{\Delta P_o}{\Delta P} = 1 - K_1 t$	$\frac{1}{q_o} \left(\frac{\Delta P_o}{\Delta P}\right)^{0.5} = \frac{1}{q_o} - \left(\frac{K_2}{2}\right) t$	$\frac{1}{q_o} \ln \left(\frac{\Delta P}{\Delta P_o}\right) = K_3 t$	$\frac{\Delta P}{\Delta P_o} = K_4 q_o^2 t + 1$

K_1, K_2, K_3, K_4: CONSTANT

q, q_o: FLOW RATE, INITIAL FLOW RATE

t = TIME OF FILTRATION

V = VOLUME OF FILTRATE

Δp, Δp_o: PRESSURE DROP, INITIAL PRESSURE DROP

FIGURE III - 1

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FIGURE III-2

CORRELATION OF FILTRATION PARAMETERS

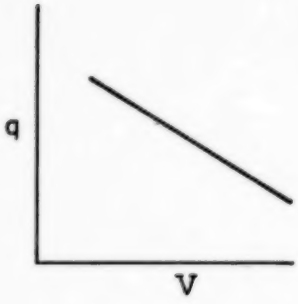
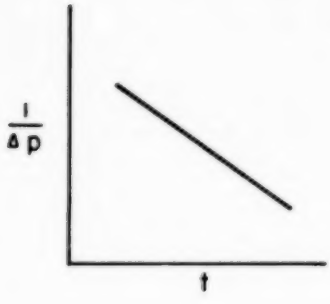
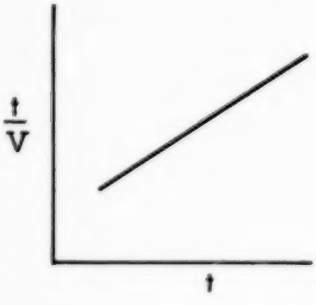
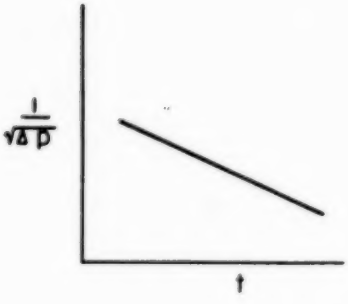
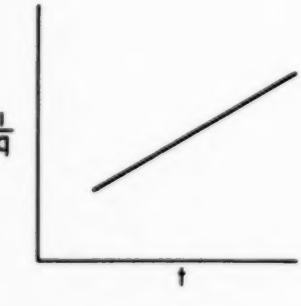
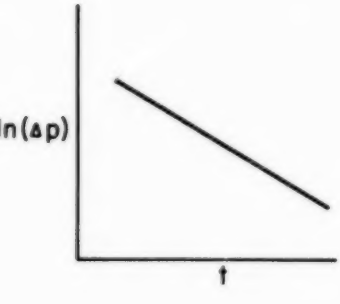
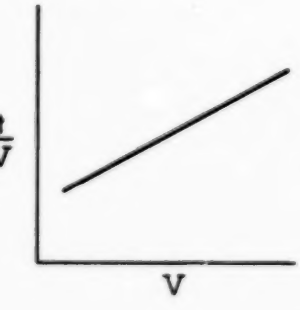
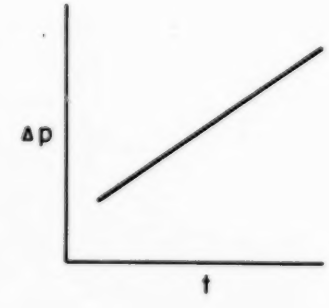
MODE OF FILTRATION	CONSTANT PRESSURE FILTRATION	CONSTANT RATE FILTRATION
COMPLETE BLOCKING		
STANDARD BLOCKING		
INTERMEDIATE BLOCKING		
CAKE FILTRATION		

FIGURE III-3

LIMITING CONDITIONS OF FILTRATION

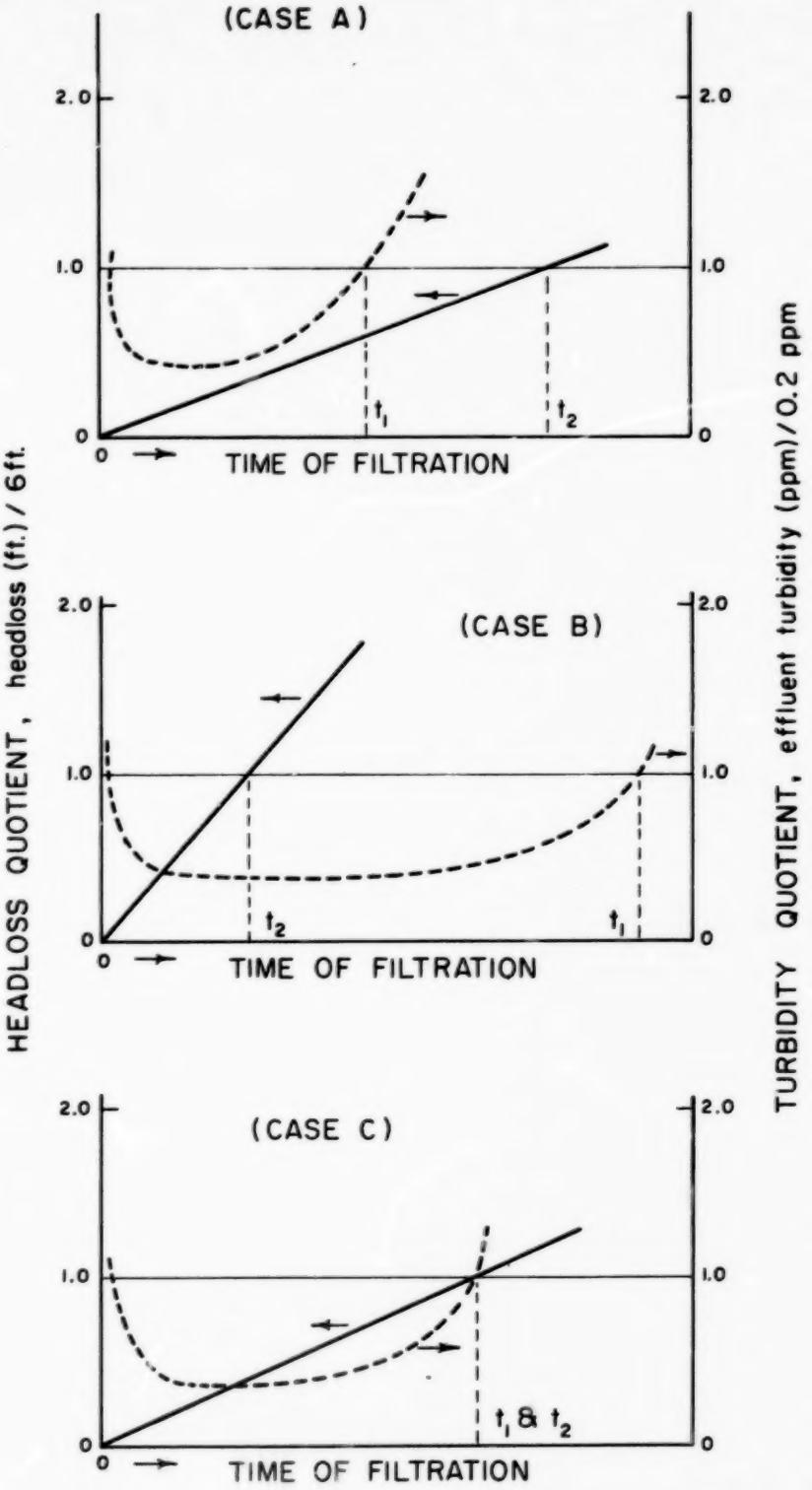
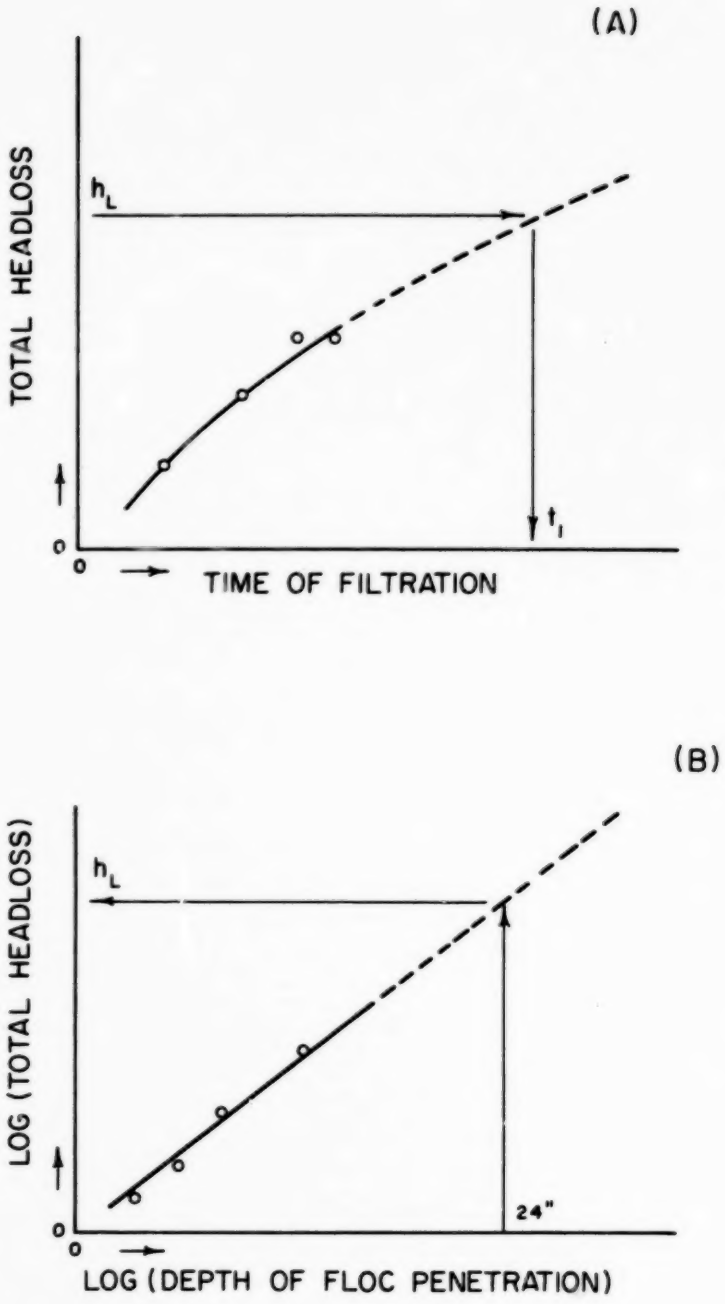


FIGURE III-4

GRAPHICAL METHOD TO DETERMINE TIME, t_1



CHAPTER IV

FIELD SURVEY OF WATER PLANTS

After investigation of the methods of floc strength measurement, a field survey of local filtration plants was made.

1. Methods of Floc Strength Measurement. Only two methods were checked in the survey and the third method of fragmented floc size was developed after the survey.

2. Method of Filterability Measurement. The result of the survey led to the development of the Filter Run Index as described earlier.

3. Pilot Plant Design Parameters. The pilot plant was planned to simulate actual water treatment plants as much as possible to obtain meaningful data. For this purpose, the data obtained from local water treatment plants were helpful.

There are five water treatment plants under East Bay Municipal Utility District (EBMUD) which supply water to the metropolitan area of Oakland. The descriptions of the four plants studied are summarized in Table IV-1.

TABLE IV-1

DESCRIPTION OF EBMUD WATER PLANTS STUDIED

Name	Sobrante	San Pablo	Upper San Leandro	Orinda
Capacity (mgd)	54	40	84	140
Raw Water Source	Local Runoff and Snow Melt	Local Runoff and Snow Melt	Local Runoff and Snow Melt	Snow Melt (Sierra Mts.)
Pretreatment Method	Coagulation and Settling	Coagulation and Settling	Coagulation and Settling	None
Liming Method	Post-filtration	Pre-filtration	Post-filtration	Post-filtration
Filter Media	Graded Sand	Graded Sand	Graded Sand	Graded Sand

METHOD OF STUDY

About a week was spent at each of the four filter plants. One filter was selected at each plant and the filtration rate was set at 3.0 gpm/sf and following data were collected.

1. The change of headloss with time.

2. The turbidity of influent and effluent of a filter at hourly intervals.

3. Core samples were collected at several depths and the amount of floc retained in the layer was determined by washing and weighing the floc.

4. The measurement of floc strength by the specific resistance and the incidental turbidity.

5. The measurement of particle mobility.

EFFECT OF LIMING METHOD ON FILTERABILITY

Among four plants investigated, only the San Pablo plant applied lime before the filtration process. Also, this plant had the best filter performance. The performance data of San Pablo plant was compared with that from the Sobrante plant as shown in Table IV-2 and Figures IV-1 and IV-2.

TABLE IV-2

COMPARATIVE PLANT OPERATION DATA
OF SAN PABLO AND SOBRANTE FILTER PLANT

	San Pablo Plant	Sobrante Plant
Raw Water Source	San Pablo Reservoir	San Pablo Reservoir
Alum Dosage	11.0 mg/l	17.2 mg/l
Turbidity of Settled Water	1.20 ppm	2.3 ppm
pH of Filter Influent	8.5	7.3
Particle Mobility	-1.03μ/sec/volt/cm	-0.51μ/sec/volt/cm
Filtration Rate	3.0 gpm/sf	3.0 gpm/sf
Duration of Filtration	92 hrs*	27 hrs
Net Headloss	3.0 ft	5.7 ft
Floc Deposit of Top 1/2"**	30.2%	60.0%
Filter Effluent Turbidity	0.05 ppm	0.05 ppm
Specific Resistance	45.1×10^{12} cm/g	1.07×10^{12} cm/g
Incremental Turbidity***	213%	55%
Filter Performance Index	5520 $\frac{\text{gallon}}{\text{sf-ft headloss}}$	1170 $\frac{\text{gallon}}{\text{sf-ft headloss}}$

* The filtration was terminated because of lack of time before reaching either limiting headloss or floc breakthrough.

** $\frac{\text{Floc deposit on top 1/2" depth}}{\text{Floc deposit} \approx \text{total bed}} \times 100$

*** The calculation is as given in equation (15). The floc was fragmented at the average shear of 26.4 dyne/cm^2.

From the results the following conclusions were obtained:

1. The San Pablo plant produced floc which is weaker than that at the Sobrante plant, as evidenced by the data on specific resistance and incremental turbidity.

2. San Pablo water after pretreatment showed longer filtration runs and deeper penetration of floc than the same at the Sobrante plant. The increase of water production per unit headloss was more than expected from the reduction of the turbidity of filter influent.

A final conclusion regarding the effect of lime cannot be drawn based on the above data, because the turbidity of the filter influent (or amount of floc) was not identical for the two plants. Therefore, another test was conducted at the San Pablo plant. On this occasion the quality of settled water was identical in two filtration runs that were also identical except for the application of lime to one of the runs. The results are shown in Table IV-3.

TABLE IV-3

THE EFFECT OF LIME ON FILTRATION

	A	B
Method of Lime Application	Before Filtration	After Filtration
Raw Water Turbidity	10 ppm	10 ppm
Alum Dosage	14.5	14.5
pH of Filter Influent	8.5	7.4
Turbidity of Filter Influent	1.8	1.8
Turbidity of Filter Effluent	~ 0.15	~ 0.15
Filtration Rate	3.0 gpm/sf	3.0 gpm/sf
Duration of Filtration Till 6 ft Headloss	85.5 hrs*	59.0 hrs**

*Average of three runs.

**Average of two runs.

From the results, it is apparent that the application of lime ahead of the filter prolonged the filtration run by 62 percent.

EFFECT OF PRETREATMENT ON FLOC PENETRATION

Orinda Filter Plant receives a very clear water which is mostly snowmelt from the Sierra Nevada mountains. The raw water, therefore, is filtered and chlorinated without pretreatment. On the other hand, Upper San Leandro (U.S.L.) water plant coagulates and settles the raw water from a local reservoir. The filtration performance of the two plants is compared as shown in Table IV-4 and Figure IV-3.

The results in Table IV-4 show the following:

1. The floc strength of the uncoagulated water is much weaker than that of coagulated water.

2. The filter performance index shows that the uncoagulated water filters better than the coagulated water. However, the relatively high effluent turbidity at the Orinda plant indicates that floc (i.e., turbidity) breakthrough was occurring.

3. The amount of floc remaining in the filter after backwashing (or residual floc) was much less for uncoagulated water. Among the three plant having alum coagulation as the pre-treatment process, the San Pablo filter showed the least residual floc as percentage of removed floc. This may be due to the weak floc produced by the addition of lime.

TABLE IV-4

FILTRATION DATA AT ORINDA
AND UPPER SAN LEANDRO WATER PLANT

	Upper San Leandro	Orinda
Raw Water		
pH	8.0	9.7
Turbidity, ppm	3.0	1.8
Alkalinity, mg/l as $CaCO_3$	87.4	22.1
Mobility, μ/sec/volt/cm	-1.07	-1.31
Settled Water		
pH	7.4	9.7
Alum Dosage, mg/l	22.2	0.0
Turbidity, ppm	0.8	1.8
Mobility, μ/sec/volt/cm	-0.81	-1.31
Specific Resistance, cm/g	26.6×10^{12}	59.1×10^{12}
Incremental Turbidity, %	69	--
Filtration		
Rate of Filtration, gpm/sf	3.0	3.0
Duration of Filtration, hrs	31.5	96.3
Net Headloss, ft	5.15	0.83
Effluent Turbidity, ppm	0.09	0.63
"Floc" Deposit on Top, 1/2" Depth, %	46.9	21.6
Filter Performance Index, gals/sf/ft headloss	1,100	20,900
Net Floc Removal, mg floc/cm^2 filter area	24.4	61.5
Residual Floc, mg floc/cm^2 filter area (after backwashing)	99.3	3.9
Residual Floc/Net Floc Removed, %*	406	6.3

*The same ratios for the San Pablo Plant Filter and the Sobrante Plant Filter were 69.0 % and 113%, respectively.

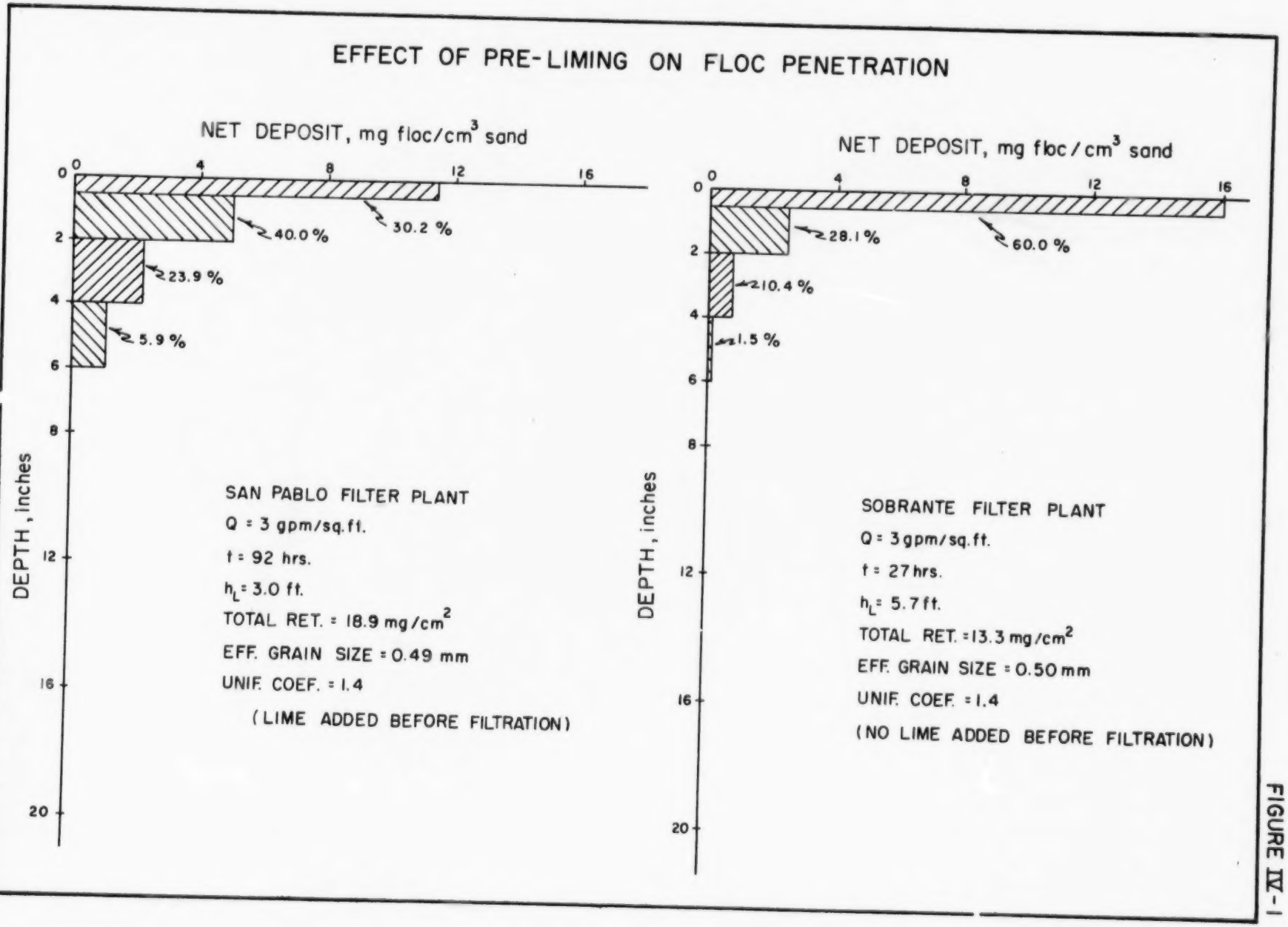

EFFECT OF PRE-LIMING ON FLOC PENETRATION
NET DEPOSIT, mg floc/cm³ sand
DEPTH, inches
0
2
4
6
8
12
16
20
40.0 %
30.2 %
23.9 %
5.9 %
SAN PABLO FILTER PLANT
Q = 3 gpm/sq.ft.
t = 92 hrs.
h_L = 3.0 ft.
TOTAL RET. = 18.9 mg/cm²
EFF. GRAIN SIZE = 0.49 mm
UNIF. COEF. = 1.4
(LIME ADDED BEFORE FILTRATION)
NET DEPOSIT, mg floc/cm³ sand
DEPTH, inches
28.1 %
60.0 %
10.4 %
1.5 %
SOBRANTE FILTER PLANT
Q = 3 gpm/sq.ft.
t = 27 hrs.
h_L = 5.7 ft.
TOTAL RET. = 13.3 mg/cm²
EFF. GRAIN SIZE = 0.50 mm
UNIF. COEF. = 1.4
(NO LIME ADDED BEFORE FILTRATION)

FIGURE IV-1

FIGURE IV-2

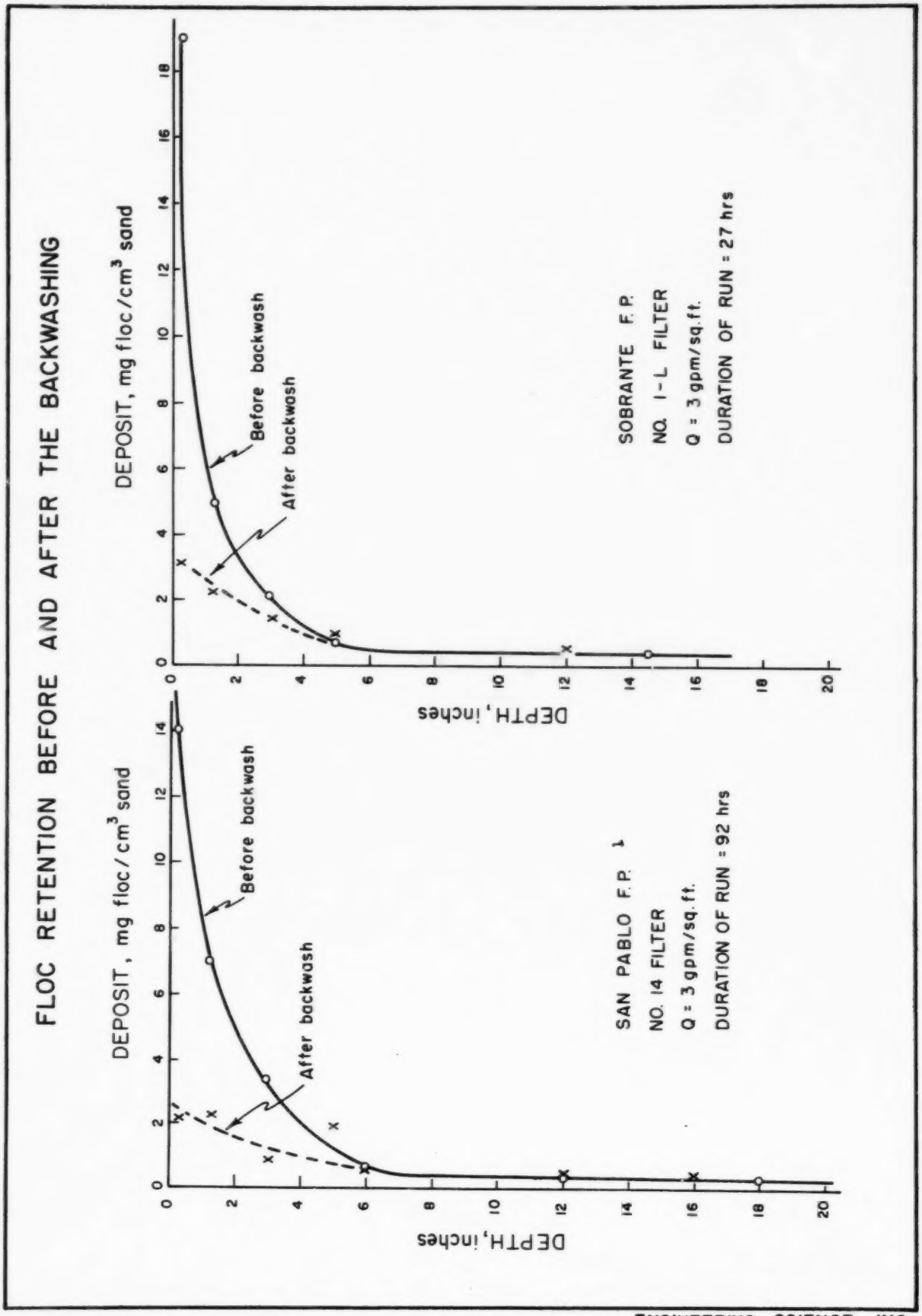
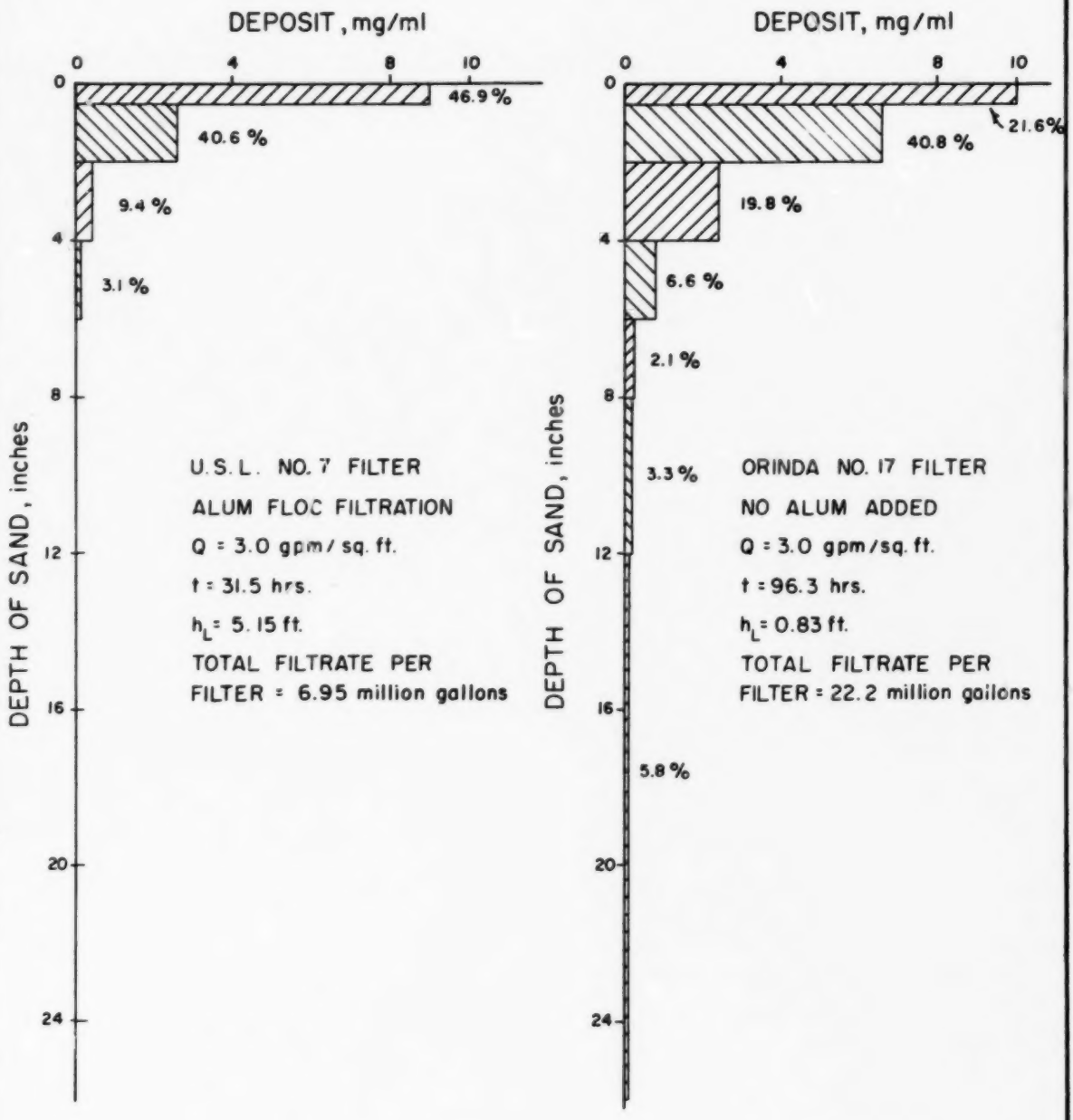

FLOC RETENTION BEFORE AND AFTER THE BACKWASHING
DEPOSIT, mg floc/cm³ sand
Before backwash
After backwash
SOBRANTE F.P.
NO. 1-L FILTER
Q = 3 gpm/sq.ft.
DURATION OF RUN = 27 hrs
DEPTH, inches
DEPOSIT, mg floc/cm³ sand
Before backwash
After backwash
SAN PABLO F.P. 1
NO. 14 FILTER
Q = 3 gpm/sq.ft.
DURATION OF RUN = 92 hrs
DEPTH, inches

FIGURE IV-3

EFFECT OF ALUM COAGULATION ON THE FLOC (OR SUSPENDED SOLID) PENETRATION



CHAPTER V

CONSTRUCTION OF PILOT PLANT

In order to characterize the filterability of a suspension by a particular filter using the Filter Run Index, construction of a pilot plant scale water treatment unit was considered necessary.

The pilot plant consists of a pretreatment unit, filtration units, and a unit to prepare synthetic suspensions.

A flow diagram of the pilot plant is shown in Figure V-1. A perikinetic coagulation unit was also constructed in parallel with the pretreatment unit. This is to evaluate the efficacy of the treatment process which omits the usual flocculation and settling step. The physical dimensions and some design criteria are shown in the following:

Flow Rate: 1.0 gpm

Constant Head Unit: 6" I.D. x 7"

Dosing Tank: 6" I.D. x 13"

Flocculation Unit:

Size: 12" x 14" x 36"
Detention time: 30 minutes
Number of chambers: three
Paddle speed: 12, 20, and 33-1/3 rpm

Settling Unit:

Size: 12" x 14" x 72"
Detention time: 46.5 minutes
Surface loading: 736 gpd/sf

Filter Units:

Size: 4" I.D. x 58"
Filtration Rate: 3.0 gpm/sf
Location of sampling ports: depth from top of filter media, 1", 2", 3", 6", 12", 17", 18", 19", 24", and 32".
Number of filters: four

Perikinetic Coagulation Unit:

Size: 2.25" x 2.25" x 50"
Number of chambers: 20
Detention time: 1.0 minute maximum

Some of the considerations given in the design of the pilot plant were:

1. Connections between each unit were made large enough so that floc would not be broken down in the process of transport.

2. In order to control the loading rate and the effluent turbidity of the settling unit, a movable tray was made. This tray can be inserted to any depth of the settling unit.

3. Flow rate control is achieved by the automatic constriction of a latex rubber tube. The device described by Ives (Reference 32) was used.

4. Backwashed water will be collected in a 50 gallon container. This water will be used for the determination of the total amount of floc detained in a filtration cycle.

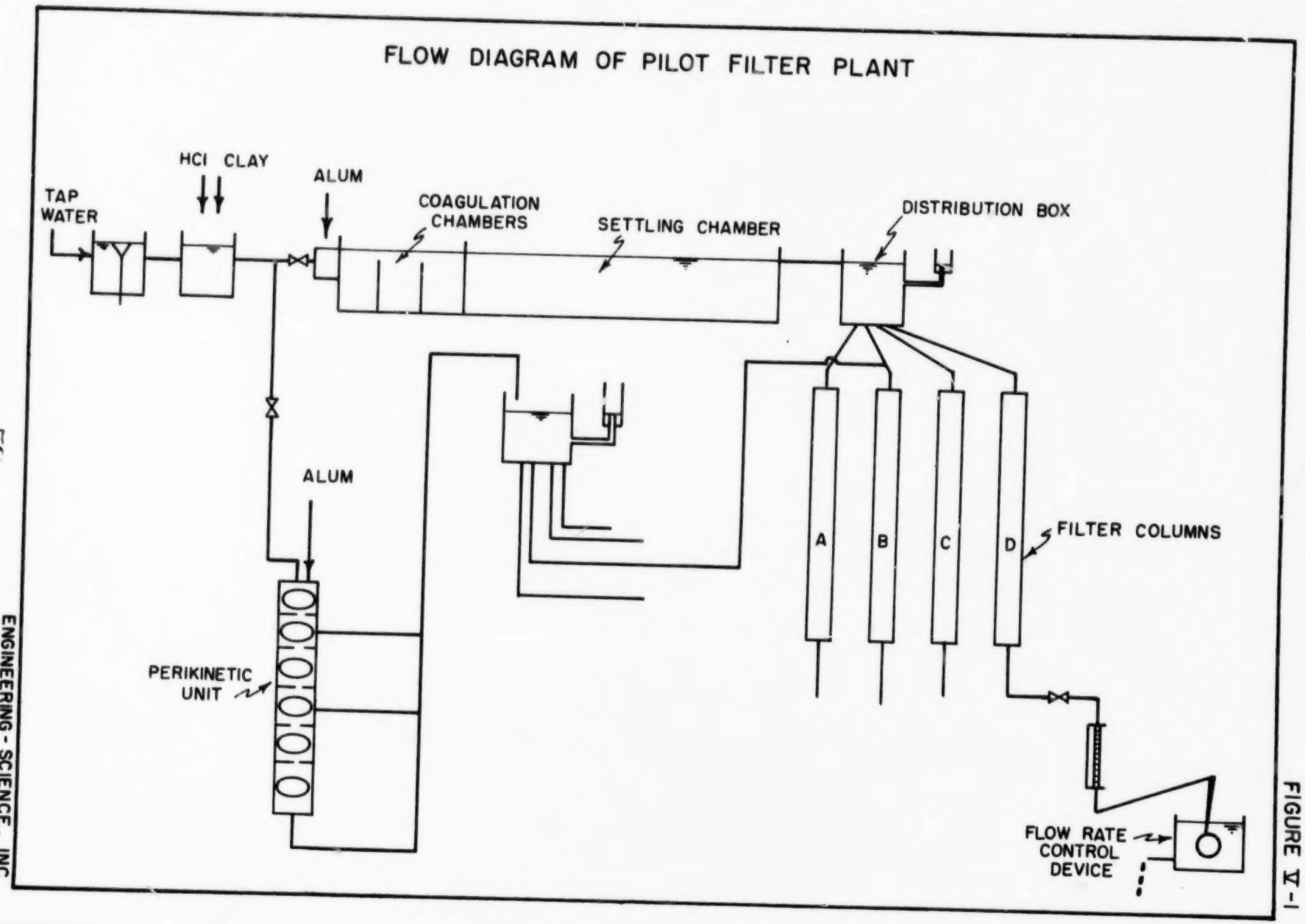

FLOW DIAGRAM OF PILOT FILTER PLANT
TAP WATER
HCl CLAY
ALUM
COAGULATION CHAMBERS
SETTLING CHAMBER
DISTRIBUTION BOX
ALUM
PERIKINETIC UNIT
A
B
C
D
FILTER COLUMNS
FLOW RATE CONTROL DEVICE

FIGURE V-1

CHAPTER VI

SUMMARY

The significance of floc strength on filterability in the depth filtration process was explored. From theoretical considerations and some water treatment plant tests, it was concluded that stronger floc does not necessarily result in better filter performance than weaker floc. The optimum strength of floc produced by alum coagulation lies at some value which results in the simultaneous occurrence of floc breakthrough and the limiting headloss.

Methods for measuring floc strength were investigated, and two methods were studied in detail. The Silting Index method is a modified permeability method which measures the decay of filtration rate at a constant pressure as the thickness of filter cake increases. The specific resistance of filter cake can be calculated from the data and is considered to represent the stiffness of floc. The second method was the median-floc-size method by which the coagulated floc is subjected to a certain shear field, and the size distribution of the resulting floc is measured by the subsidence rate. The median size of the sheared floc was selected to characterize floc strength because the stronger the floc the less the breakdown should be.

The two methods developed were evaluated on alum floc suspensions. The significant effects of coagulation pH and alum dosage on the specific resistance and the median floc size were observed. However, for reasons which are not clear, the two methods did not give the same results. Considering the definition of floc strength, the second method appears to be more appropriate.

In order to establish quantitative correlation between floc strength and filter performance, methods of measuring filterability of floc were explored. On a given filter media, a rational measure of filter performance was considered to be the time difference between t_1 and t_2, where t_1 represents the time of floc breakthrough and t_2 the time when limiting headloss is reached. To overcome the floc concentration effect, the time difference (t_1-t_2) is normalized by dividing by (t_1+t_2). Therefore the proposed index, designated as Filter Run Index, is defined as follows:

$$\text{Filter Run Index} = \frac{t_1-t_2}{t_1+t_2}$$

According to the index the zero value corresponds to the best filter performance, while positive or negative values indicate premature termination of the filter run due to strong or weak floc. Methods to measure the two time factors (t_1 and t_2) were described, and the necessity of running pilot plant filters to obtain data was noted.

In order to obtain design data for a pilot plant and also to evaluate the effect of floc strength on actual filter performance, several local water treatment plants were studied. The application of lime ahead of a filter resulted in a marked increase in the filtration run. The penetration of alum floc was much less than the penetration of uncoagulated solids. For alum coagulated waters, the amount of floc remaining on filters after backwashing was the least with lime treated water.

These observations were attributed to the strength of floc.

A pilot plant was designed to obtain quantitative correlation between floc strength and filterability under controlled conditions. The capacity of the plant is 1.0 gallon per minute. It has coagulation and settling units for conventional pretreatment, four filter columns four inches in inside diameter, and a pretreatment device which can bypass the settling unit. The pilot plant will be operated during the next project year.

APPENDIX A

CALCULATION OF SHEAR STRESS IN A CAPILLARY TUBE

Analysis of laminar flow in a pipe line is given as follows (Reference 33)

$$\tau = -\mu \frac{dv}{dr} \tag{1}$$

$$\tau = \frac{g\rho h}{2l} \times r \tag{2}$$

From (1) and (2)

$$\frac{dv}{dr} = -\frac{1}{\mu} \tau = -\frac{1}{\mu} \frac{g\rho h}{2l} \times r \tag{3}$$

Upon integration

$$v = V_{max} - \frac{g\rho}{4\mu} \cdot \frac{h}{l} r^2 \tag{4}$$

$$V_{max} = \frac{g\rho}{4\mu} \cdot \frac{h}{l} r_o^2 \tag{5}$$

$$V_{ave} = \frac{V_{max}}{2} = \frac{g\rho}{8\mu} \cdot \frac{h}{l} r^2 \tag{6}$$

$$\therefore \quad \frac{h}{l} = \frac{V_{ave}}{r_o^2} \cdot \frac{8\mu}{g\rho} \tag{7}$$

$$\tau_{ave} = \frac{2}{3} \tau_{max} = \frac{2}{3} \cdot \frac{g\rho}{2} \cdot \frac{h}{l} r_o \tag{8}$$

$$\therefore \quad \frac{h}{l} = \frac{\tau_{ave}}{r_o} \cdot \frac{3}{g\rho} \tag{9}$$

From 7 and 9

$$\tau_{ave} = \frac{8}{3} \cdot \mu \frac{V_{ave}}{r_o} = \frac{8}{3} \frac{\mu}{r_o} \cdot \left(\frac{Q}{A} \right) \tag{10}$$

From equation (10) it is shown that the average shear stress can be calculated from the measurement of flow rate, and the cross sectional area and radius of the capillary tube.

τ = shear stress

τ_{ave} = average shear stress

μ = viscosity

v = velocity

V_{max} = maximum velocity

V_{ave} = average velocity

r = radius of an imaginary tube

r_o = radius of the capillary tube

g = gravity constant

ρ = density of liquid

l = length of capillary

h = headloss

Q = flow rate of liquid

A = cross sectional area of the capillary

APPENDIX B

CALCULATION OF PARTICLE SIZE BY STOKE'S LAW

Stoke's law states:

$$V = \frac{g}{18} \cdot \frac{\rho_f - \rho}{\mu} \cdot d^2 \qquad (1)$$

$$V = \frac{l}{t} \qquad (2)$$

$$\therefore \quad d = \left(\frac{l}{t} \cdot \frac{18\mu}{g} \cdot \frac{1}{\rho_f - \rho} \right)^{1/2} \qquad (3)$$

$$= \left(\frac{K}{t} \right)^{1/2} \qquad (4)$$

$$\text{when} \quad K = \frac{18 \cdot \mu \cdot l}{g\ (\rho_f - \rho)} \qquad (5)$$

V = settling velocity

g = gravity constant

ρ_f = density of floc

ρ = density of medium

μ = viscosity

d = particle diameter

l = length of fall

t = time of fall

K = constant

On a given condition of measurement, value of "K" can be calculated and the particle diameter is proportional to $1/\sqrt{t}$, and the diameter of the particle can be calculated by equation (4).

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